COEFFICIENT OF THERMAL AND MOISTURE EXPANSION
OF CONCRETE USED IN FLORIDA

BY

GABRIEL D. ALUNGBE

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE
UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1989

Dedicated to the loving memory of my father, Mr. Awusa Oshen,

who passed away while I was still a fetus.

ACKNOWLEDGEMENTS

I extend a special acknowledgement to Dr. Mang Tia who served in the capacity of chairman of my supervisory committee. He meticulously guided me and provided copious support through the entire stages of th project. His counsel was unparalleled. Dr. David G. Bloomquist, co-chairman of my supervisory committee, provided myriad hours of support and guidance. Special thanks are extended to him. Further gratitude is extended to Dr. Byron E. Ruth, Mr. Torbjorn (Toby) J. Larsen, and Dr. Andrawus I. Khuri for having given generously of their expertise and time and for serving on my supervisory committee.

This project would not have been possible without the financial support provided by the Florida Department of Transportation (FDOT). They also provided some materials used in this project. I unequivocally say thank you. To Dr. Jamshid Armaghani and Mr. Toby Larsen both of Materials Office (formerly Bureau of Materials and Research) at FDOT Gainesville, who worked incessantly for the approbation of this project, I am very grateful.

I would like to thank all the students and engineering technicians who assisted me in this research, and all my friends, especially Prasit Soongswang, whose assistance contributed to the successful completion of this project.

Mr. Daniel Richardson fabricated some of the equipments used in this research. To him I say thank you very much. A special thank you

is also extended to the incomparable Mrs. Irene R. Scarso who meticulously and skillfully typed the manuscript.

Finally, I would like to thank my mother and grandmother, Mrs. Victoria E. Ebagu and Ms. Omaku Odugbo, respectively. Their enduring support and guidance are highly appreciated. And I thank my uncles Messrs. Nathy A. Oshen and Linus E. Okom for their support. To the governments of the Cross River State and Federal Republic of Nigeria who financed my bachelor's and master's studies, my heartfelt thanks are extended. I also acknowledge God for making all this possible.

TABLE OF CONTENTS

PAGE

ACKNOWLEDGEMENTS....iii
LIST OF TABLES....viii
LIST OF FIGURES....xv
ABSTRACT....xix

CHAPTER

1 INTRODUCTION....1
  1.1 Background....1
  1.2 Objectives of the Study....[illegible]
2 LITERATURE REVIEW....4
  2.1 Thermal Properties....4
  2.2 Test Methods....12
  2.3 Factors Affecting Coefficient of Thermal Expansion of Concrete....21
  2.4 Effects of Thermal Expansion on Pavements....29
3 DEVELOPMENT OF A LABORATORY TESTING PROCEDURE FOR MEASURING LENGTH CHANGE OF CONCRETE....30
  3.1 Introduction....30
  3.2 Test Equipment....31
  3.3 Test Specimens....[illegible]
  3.4 Test Procedures....[illegible]
4 TESTING PROGRAM....46
  4.1 Laboratory Testing Program....46
  4.2 Study of In-Service Concrete....55
5 MATERIALS....57
  5.1 Cements....57
  5.2 Aggregates....57
  5.3 Admixtures....64
  5.4 Epoxy....64

6 EXPERIMENTAL DESIGNS OF THE LABORATORY STUDY..................67

6.1 Introduction..67
6.2 Design No. 1..69
6.3 Design No. 2..70
6.4 Design No. 3..70
6.5 Design No. 4..74
6.6 Design No. 5..74
6.7 Design No. 6..74
6.8 Design No. 7..78

7 COMPRESSIVE STRENGTH OF LABORATORY CONCRETE SPECIMENS.........80

7.1 Introduction..80
7.2 Experimental Results......................................80
7.3 Analysis of Results.......................................8[illegible]
7.4 Summary of Findings.......................................108

8 SPLITTING TENSILE STRENGTH OF LABORATORY CONCRETE SPECIMENS..118

8.1 Introduction..118
8.2 Analysis of Results.......................................118
8.3 Summary of Findings.......................................140

9 MODULUS OF RUPTURE OF LABORATORY CONCRETE SPECIMENS..........141

9.1 Introduction..141
9.2 Analysis of Results.......................................141
9.3 Summary of Findings.......................................163

10 STATIC MODULUS OF ELASTICITY OF LABORATORY CONCRETE SPECIMENS..164

10.1 Introduction...164
10.2 Analysis of Results......................................164
10.3 Summary of Findings......................................188

11 COEFFICIENT OF LINEAR THERMAL EXPANSION OF LABORATORY CONCRETE SPECIMENS...189

11.1 Introduction...189
11.2 Experimental Results.....................................189
11.3 Analysis of Results......................................189
11.4 Summary of Findings......................................214

12 COEFFICIENT OF MOISTURE EXPANSION OF LABORATORY CONCRETE SPECIMENS..215

12.1 Introduction...215
12.2 Calculation of Coefficient of Moisture Expansion.......215
12.3 Analysis of Results......................................218
12.4 Summary of Findings......................................222

13 RESULTS OF IN-SERVICE CONCRETE STUDY....229

13.1 Introduction....229
13.2 Compressive Strength Test Results....229
13.3 Splitting Tensile Strength Test Results....232
13.4 Static Modulus of Elasticity Test Results....236
13.5 Results of Linear Thermal Expansion on In-Service Concrete....236
13.6 Results of Moisture Expansion of In-Service Concrete...243
13.7 Graphical Representation of Means....246
13.8 Summary of Findings....246

14 DEVELOPMENT OF PREDICTION EQUATIONS FOR CONCRETE PROPERTIES..254

14.1 Introduction....254
14.2 Relationship Between the Compressive and Splitting Tensile Strengths....255
14.3 Relationship Between the Compressive Strength and Modulus of Rupture....257
14.4 Relationship Between the Compressive Strength and Static Modulus of Elasticity....261
14.5 Relationship Between the Splitting Tensile Strength and Modulus of Rupture....264
14.6 Prediction of Coefficient of Linear Thermal Expansion of Concrete....2[illegible]
14.7 Prediction of Coefficient of Moisture Expansion....273
14.8 Summary of Findings....273

15 OPTIMIZATION OF CONCRETE MIX DESIGN FOR CONCRETE PAVEMENT....277

15.1 Introduction....277
15.2 Effects of Thermal Expansion and Modulus of Elasticity of Concrete....279
15.3 Optimizing Concrete Pavement Mix Design....281

16 CONCLUSIONS AND RECOMMENDATIONS....288

16.1 Introduction....288
16.2 Conclusions....288
16.3 Recommendations....297
16.4 Recommendations for Further Research....297

APPENDICES

A MIX PROPORTIONS OF CONCRETE MIXES....300

B PROPERTIES OF FRESH CONCRETE....303

C LENGTH READINGS OF WATER-SATURATED LABORATORY CONCRETE SPECIMENS....306

D LENGTH READINGS OF OVEN-DRIED LABORATORY CONCRETE SPECIMENS....312

E LENGTH READINGS OF PARTIALLY-SATURATED LABORATORY CONCRETE SPECIMENS....318

F LENGTH READINGS OF WATER-SATURATED IN-SERVICE CONCRETE SPECIMENS....335

G LENGTH READINGS OF OVEN-DRIED IN-SERVICE CONCRETE SPECIMENS....338

H LENGTH READINGS OF PARTIALLY-SATURATED IN-SERVICE CONCRETE SPECIMENS....342

REFERENCES....346

SUPPLEMENTARY BIBLIOGRAPHY....350

BIOGRAPHICAL SKETCH....357

LIST OF TABLES

TABLE PAGE

2.1 Change in Moisture Content and Corresponding Change in Length as Reported by Matsumoto....16

2.2 Properties of Concrete Mixes Used by Saemann and Washa....19

2.3 Reported Coefficients of Linear Thermal Expansion of Various Rocks....23

2.4 Reported Coefficients of Linear Thermal Expansion of a Few More Important Rock Minerals....24

3.1 Typical Length Readings for Four Different Environmental Conditions....44

4.1 Mix Combinations for the Laboratory Study....46

4.2 Tests to be Performed on Each Batch of Concrete....49

5.1 Results of Physical Tests on Cement Used....58

5.2 Results of Chemical Analyses on Cement Used....59

5.3 Physical Properties of Coarse Aggregates....60

6.1 Factors, Levels, and Interactions for the Partial Factorial Experiment....68

6.2 Design for Test on Effects of Aggregate Type, W/C Ratio at Variable Cement Content, and Curing Duration (Design No. 1)...71

6.3 Design for Test on Effects of Aggregate Type and Curing Duration at W/C of 0.53 and Cement Content of 508 lb/cy (Design No. 2)....72

6.4 Design for Test on Effects of Aggregate Type and Curing Duration at W/C of 0.45 and Cement Content of 564 lb/cy (Design No. 3)....73

6.5 Design for Test on Effects of Aggregate Type and Curing Duration at W/C of 0.33 and Cement Content of 752 lb/cy (Design No. 4)....75

6.6 Design for Test on Effects of Cement Content and Curing Duration Given W/C of 0.53 and Brooksville Limestone (Design No. 5)....76

6.7 Design for Test on Effects of Cement Content and Curing Duration Given W/C of 0.45 and Brooksville Limestone (Design No. 6)....77

6.8 Design for Test on Effects of W/C Ratio and Curing Duration Given Brooksville Limestone and Cement Content of 658 lb/cy (Design No. 7)....79

7.1 Results of Compressive Strength Test on Hardened Concrete....81

7.2 Expected Mean Square Algorithm for Design No. 1....8

7.3 Expected Mean Square Algorithm for Design Nos. 2 - 4....90

7.4 Expected Mean Square Algorithm for Design Nos. 5 and 6....91

7.5 Expected Mean Square Algorithm for Design No. 7....92

7.6 Results of ANOVA on Data From Compressive Strength Test in Design No. 1....95

7.7 Grouping of Aggregate Type by Means of Compressive Strength of Concrete From Duncan's Test (Design No. 1)....96

7.8 Grouping of Water-Cement Ratio by Means of Compressive Strength of Concrete From Duncan's Test (Design No. 1)....97

7.9 Grouping of Curing Duration by Means of Compressive Strength of Concrete From Duncan's Test (Design No. 1)....98

7.10 Results of ANOVA on Data From Compressive Strength Test in Design No. 2....100

7.11 Grouping of Aggregate Type by Means of Compressive Strength of Concrete From Duncan's Test (Design No. 2)....101

7.12 Results of ANOVA on Data From Compressive Strength Test in Design No. 3....102

7.13 Grouping of Aggregate Type by Means of Compressive Strength of Concrete From Duncan's Test (Design No. 3)....104

7.14 Results of ANOVA on Data From Compressive Strength Test in Design No. 4....105

7.15 Grouping of Aggregate Type by Means of Compressive Strength of Concrete From Duncan's Test (Design No. 4)....106

7.16 Results of ANOVA on Data From Compressive Strength Test in Design No. 5..107

7.17 Results of ANOVA on Data From Compressive Strength Test in Design No. 6..109

7.18 Results of ANOVA on Data From Compressive Strength Test in Design No. 7..110

8.1 Results of Splitting Tensile Strength Test on Hardened Concrete..120

8.2 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 1..122

8.3 Grouping of Aggregate Type by Means of Splitting Tensile Strength of Concrete From Duncan's Test (Design No. 1).......123

8.4 Grouping of Water-Cement Ratio by Means of Splitting Tensile Strength of Concrete From Duncan's Test (Design No. 1).......124

8.5 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 2..125

8.6 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 3..127

8.7 Grouping of Aggregate Type by Means of Splitting Tensile Strength of Concrete From Duncan's Test (Design No. 3).......128

8.8 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 4..129

8.9 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 5..130

8.10 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 6..132

8.11 Results of ANOVA on Data From Splitting Tensile Strength Test in Design No. 7..133

9.1 Results of Moduli of Rupture Test on Hardened Concrete.......142

9.2 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 1..145

9.3 Grouping of Aggregate Type by Means of Modulus of Rupture of Concrete From Duncan's Test (Design No. 1)................146

9.4 Grouping of Water-Cement Ratio by Means of Modulus of Rupture of Concrete From Duncan's Test (Design No. 1)................147

9.5 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 2..149

9.6 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 3..150

9.7 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 4..151

9.8 Grouping of Aggregate Type by Means of Modulus of Rupture of Concrete From Duncan's Test (Design No. 4)................152

9.9 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 5..154

9.10 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 6..155

9.11 Results of ANOVA on Data From Modulus of Rupture Test in Design No. 7..156

10.1 Results of Modulus of Elasticity Test on Hardened Concrete..165

10.2 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 1..167

10.3 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete From Duncan's Test (Design No. 1)................168

10.4 Grouping of Water-Cement Ratio by Means of Modulus of Elasticity of Concrete From Duncan's Test (Design No. 1)........169

10.5 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 2..171

10.6 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete From Duncan's Test (Design No. 2)................172

10.7 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 3..173

10.8 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete From Duncan's Test (Design No. 3)................174

10.9 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 4..176

10.10 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete From Duncan's Test (Design No. 4)................177

10.11 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 5..178

10.12 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 6....179

10.13 Results of ANOVA on Data From Modulus of Elasticity Test in Design No. 7....181

11.1 Results of Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimens....190

11.2 Results of Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens....192

11.3 Result of PROC MEANS on Paired Comparison of Single Sample Groups....195

11.4 Mean, Standard Error of the Mean, and 95% Comfidence Inteval of Coefficient of Thermal Linear Expansion Results....196

11.5 Results of ANOVA on Data From Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimen in Design No. 1....199

11.6 Grouping of Aggregate Type by Means of Coefficient of Linear Thermal Expansion of Water-Saturated Concrete From Duncan's Test (Design No. 1)....20

11.7 Results of ANOVA on Data From Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimen in Design No. 5....201

11.8 Results of ANOVA on Data From Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimen in Design No. 6....202

11.9 Results of ANOVA on Data From Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens in Design No. 1....206

11.10 Grouping of Aggregate Type by Means of Coefficient of Linear Thermal Expansion of Oven-Dried Concrete From Duncan's Test (Design No. 1)....208

11.11 Results of ANOVA on Data From Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens in Design No. 5....209

11.12 Results of ANOVA on Data From Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens in Design No. 6....210

12.1 Results of Moisture Expansion of Concrete Specimens....216

12.2 Results of ANOVA on Data From Moisture Expansion of Concrete Specimens in Design No. 3....219

12.3 Grouping of Aggregate Type by Means of Coefficient of Moisture Expansion From Duncan's Test (Design No. 1)....220

12.4 Results of ANOVA on Data From Moisture Expansion of Concrete in Design No. 5....221

12.5 Results of ANOVA on Data From Moisture Expansion of Concrete in Design No. 6....223

12.6 Results of ANOVA on Data From Moisture Expansion of Concrete in Design No. 7....224

13.1 Sites of In-Service Concrete Pavement Study....230

13.2 Compressive Strength of In-Service Pavement Concrete....231

13.3 Mean Splitting Tensile Strength of In-Service Pavement Concrete....233

13.4 Modulus of Elasticity of In-Service Pavement Concrete....237

13.5 Comparison of Measured and Estimated Static Moduli of Elasticity of Concrete....238

13.6 Results of Coefficient of Linear Thermal Expansion Test on Water-Saturated In-Service Concrete....239

13.7 Results of Coefficient of Linear Thermal Expansion Test on Oven-Dried In-Service Concrete....241

13.8 Results of T Test on the Difference Between the Coefficient of Thermal Expansion at Water-Saturated and Oven-Dried Conditions....244

13.9 Results of Moisture Expansion Test on In-Service Concrete...245

14.1 Regression Coefficients for Relation Between Compressive and Splitting Tensile Strength at 28-Day Moist Curing....256

14.2 Regression Coefficients for Relation Between Compressive and Modulus of Rupture at 28-Day Moist Curing....260

14.3 Regression Coefficients for Relation Between Compression Strength and Static Modulus of Elasticity at 28-Day Moist Curing....263

14.4 Regression Coefficients for Relation Between the Splitting Tensile Strength and Modulus of Rupture at 28-Day Moist Curing....267

14.5 Coefficient of Linear Thermal Expansion of Water-Saturated Laboratory Concrete Per Strength Class....270

14.6 Coefficient of Linear Thermal Expansion of Oven-Dried Laboratory Concrete Per Strength Class.........................271

14.7 Combined Water-Saturated and Oven-Dried Coefficient of Linear Thermal Expansion of Laboratory Concrete Specimens Per Strength Class..272

14.8 Coefficient of Moisture Expansion of Laboratory Concrete Per Strength Class..274

14.9 Coefficient of Moisture Expansion of In-Service Concrete....275

15.1 Computed Maximum Longitudinal Stress Using FEACONS IV Program..282

15.2 Computed Maximum Load-Induced Stresses and Stress Ratios Using Mean 28-Day Values of Modulus of Rupture, Modulus of Elasticity, and Water-Saturated Coefficient of Thermal Expansion of Laboratory Concrete...........................286

16.1 Range of Coefficient of Linear Thermal Expansion of Water-Saturated Laboratory Concrete...............................292

16.2 Range of Coefficient of Linear Thermal Expansion of Oven-Dried Laboratory Concrete...................................293

16.3 Range of Coefficient of Linear Thermal Expansion of Laboratory Concrete at Water-Saturated and Oven-Dried Conditions..294

16.4 Range of Coefficient of Moisture Expansion of Laboratory Concrete...295

16.5 Range of Coefficient of Moisture Expansion of In-Service Concrete...296

LIST OF FIGURES

FIGURE PAGE

2.1 Uniform Expansion of Concrete....................................6

2.2 Linear Expansion of Solid..7

3.1 Length Comparator...32

3.2 Water Tank..34

3.3 Forced Draft Oven...36

3.4 Specimen Mold...37

3.5 Concrete Specimen with Embedded Thermocouples..................39

5.1 Gradation Chart for Brooksville Limestone #89 Coarse Aggregate Used in Batches 1-12 [30]............................61

5.2 Gradation Chart for Calera Coarse Aggregate [28]...............62

5.3 Gradation Chart for the River Gravel Coarse Aggregate [28]...63

5.4 Gradation Chart for Goldhead Sand Used in Batches 1-19 [28]...65

5.5 Gradation Chart for Goldhead Sand Used in Batches 20-24......66

7.1 Influence of Water/Cement Ratio and Moist Curing Duration on Concrete Strength Using Brooksville Limestone...............111

7.2 Influence of Water/Cement Ratio and Moist Curing Duration on Concrete Strength Using Dense Limestone.....................112

7.3 Influence of Water/Cement Ratio and Moist Curing Duration on Concrete Strength Using River Gravel........................113

7.4 Influence of Aggregate Type and Moist Curing Duration on Concrete Strength at W/C = 0.33..............................114

7.5 Influence of Aggregate Type and Moist Curing Duration on Concrete Strength at W/C = 0.45..............................115

7.6 Influence of Aggregate Type and Moist Curing Duration on Concrete Strength at W/C = 0.53..............................116

3.1 Influence of Water/Cement Ratio and Moist Curing Duration on Splitting Tensile Strength of Concrete Using Brooksville Limestone..134

8.2 Influence of Water/Cement Ratio and Moist Curing Duration on Splitting Tensile Strength of Concrete Using Dense Limestone..135

8.3 Influence of Water/Cement Ratio and Moist Curing Duration on Splitting Tensile Strength of Concrete Using River Gravel..136

8.4 Influence of Aggregate Type and Moist Curing Duration on Splitting Tensile Strength of Concrete at W/C = 0.33........137

8.5 Influence of Aggregate Type and Moist Curing Duration on Splitting Tensile Strength of Concrete at W/C = 0.45........138

8.6 Influence of Aggregate Type and Moist Curing Duration on Splitting Tensile Strength of Concrete at W/C = 0.53........139

9.1 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Rupture of Concrete Using Brooksville Limestone..157

9.2 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Rupture of Concrete Using Dense Limestone.....158

9.3 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Rupture of Concrete Using River Gravel........159

9.4 Influence of Aggregate Type and Moist Curing Duration on Modulus of Rupture of Concrete at W/C = 0.33................160

9.5 Influence of Aggregate Type and Moist Curing Duration on Modulus of Rupture of Concrete at W/C = 0.45................1

9.6 Influence of Aggregate Type and Moist Curing Duration on Modulus of Rupture of Concrete at W/C = 0.53................162

10.1 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Elasticity of Concrete Using Brooksville Limestone..182

10.2 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Elasticity of Concrete Using Dense Limestone.....183

10.3 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Elasticity of Concrete Using River Gravel........184

10.4 Influence of Aggregate Type and Moist Curing Duration on Modulus of Elasticity of Concrete at W/C = 0.33.............185

10.5 Influence of Aggregate Type and Moist Curing Duration on Modulus of Elasticity of Concrete at W/C = 0.45.............186

10.6 Influence of Aggregate Type and Moist Curing Duration on Modulus of Elasticity of Concrete at W/C = 0.53.............187

11.1 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Water-Saturated Concrete at W/C = 0.33..203

11.2 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Water-Saturated Concrete at W/C = 0.45..204

11.3 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Water-Saturated Concrete at W/C = 0.53..205

11.4 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Oven-Dried Concrete at W/C = 0.33..211

11.5 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Oven-Dried Concrete at W/C = 0.45..21

11.6 Influence of Aggregate Type and Moist-Curing Duration on Coefficient of Expansion of Oven-Dried Concrete at W/C = 0.53..213

12.1 Influence of Aggregate Type and Moist-Curing Duration on the Coefficient of Moisture Expansion of Concrete at W/C = 0.33..225

12.2 Influence of Aggregate Type and Moist-Curing Duration on the Coefficient of Moisture Expansion of Concrete at W/C = 0.45..226

12.3 Influence of Aggregate Type and Moist-Curing Duration on the Coefficient of Moisture Expansion of Concrete at W/C = 0.53..227

13.1 Mean Compressive Strength of In-Service Concrete Pavement...247

13.2 Mean Splitting Tensile Strength of In-Service Concrete Pavement...248

13.3 Mean Modulus of Elasticity of In-Service Concrete Pavement...249

13.4 Mean Water-Saturated Coefficient of Linear Thermal Expansion of In-Service Concrete Pavement..............................250

13.5 Mean Oven-Dried Coefficient of Linear Thermal Expansion of In-Service Concrete Pavement....251

13.6 Mean Coefficient of Moisture Expansion of In-Service Concrete Pavement....252

14.1 Plot of Splitting Tensile Strength Versus Compressive Strength....258

14.2 Plot of Flexural Strength Versus Compressive Strength....262

14.3 Relationship Between Elastic Modulus and Compressive Strength....265

14.4 Relationship Between Splitting Tensile Strength and Flexural Strength....26

15.1 Curling of Concrete Pavement Due to Temperature Differential [39]....278

15.2 Effect of Concrete Modulus on Maximum Stresses Caused by a 22-Kip Axle Load and a Temperature Differential of +20°F [40]....280

15.3 Computed Maximum Longitudinal Stress Using FEACONS IV Program....283

15.4 Combinations of Modulus of Elasticity and Coefficient of Thermal Expansion of Concrete to Produce Fixed Maximum Stresses....284

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

COEFFICIENT OF THERMAL AND MOISTURE EXPANSION OF CONCRETE USED IN FLORIDA

By

Gabriel D. Alungbe

December 1989

Chairman: Dr. Mang Tia
Cochairman: Dr. David Bloomquist
Major Department: Civil Engineering

A research study was conducted using laboratory-batched and in-service concrete specimens to determine the coefficient of linear thermal and moisture expansion of concrete used in Florida at temperatures ranging from 77 to 140°F (25 to 60°C).

Twenty-four concrete mixtures were prepared with three types of aggregates, namely Brooksville limestone, dense limestone, and river gravel. The former two are porous Florida aggregates while the latter is a nonporous aggregate obtained from Alabama. A type II Portland cement was used at a content of 508 lb/cy (W/C = 0.53), 564 lb/cy (W/C = 0.45), and 752 lb/cy (W/C = 0.33) for all the three types of aggregates and an additional 564 lb/cy (W/C = 0.53), 658 lb/cy (W/C = 0.45), and 658 lb/cy (W/C = 0.38) for Brooksville limestone. The laboratory-batched concrete specimens were moist-cured and tested at 28 and 90 days. The in-service concrete core samples obtained from eleven project sites in Florida were prepared and tested as received.

Compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity tests were performed on at least three specimens per batch per curing age of the laboratory concrete. The tests were also performed on concrete core samples from a few existing concrete pavements in Florida.

About two hundred 3" x 3" x 11 1/4" laboratory and 3" x 3" x 9" in-service concrete prisms were tested for thermal and moisture coefficient of expansion at water-saturated, partially-saturated, and oven-dried conditions. The coefficient of thermal expansion was affected by the aggregate types, curing age, and moisture conditions at measurement. The concretes made with Brooksville aggregate had the lowest coefficient of thermal expansion and those made with river gravel had the highest. The concrete made with dense limestone had an intermediate coefficient of thermal expansion. The water-saturated laboratory concrete had lower coefficients of thermal expansion than the oven-dried concrete. However, the water-saturated in-service concrete had higher coefficients of thermal expansion than the oven-dried in-service concrete. The coefficient of thermal expansion of oven-dried concrete specimens decreased with moist-cured age. No significant difference was observed in water-saturated concrete specimens. The coefficient of moisture expansion decreased with age.

Parameters of concrete mixes which affect the performance of concrete pavements were analyzed. A method for evaluation of concrete mixtures for pavement construction was developed and presented.

CHAPTER 1
INTRODUCTION

1.1 Background

In the past few years, great progress has been made in the analysis and evaluation of concrete pavement response and performance through th cooperative efforts of the FDOT Materials Office and the University of Florida. Through field testing and analysis using the recently developed finite element program, FEACONS III, it has been determined that the two critical stress conditions occur when (1) a load is applied at the edge of a slab at midday when the slab is curled upward at the center, and (2) a load is applied near the slab corner at midnight or early morning when the slab is curled upward at the joints and edges. The critical stress conditions could be worsened by the presence of in-plane stresses caused by overall thermal changes and constraints at the joints and edges. While the analytical tools for determining the critical stresses in a pavement system have been developed, the accuracy the computer results would depend on the accuracy of the input parameters. One area of uncertainty in the input parameters is the coefficient of linear thermal expansion of the concrete.

The coefficient of thermal expansion of concrete is listed in the literature as varying from 4 to 8 millionths per °F (7.2 to 14.4 millionths per °C), and is influenced primarily by the character of the aggregate and secondarily by the characteristics of the cement paste.

Data on Florida concrete are lacking. In the absence of actual data, a value of 6 millionths per °F is usually assumed. This could result in an error of 30% in the coefficient of thermal expansion and errors of more than 100% in the computed stresses.

The effects of length change of concrete due to moisture variation are similar to those due to temperature variation. If there existed a moisture gradient within a concrete slab, the slab could warp in a similar manner as the slab would curl due to a temperature gradient. Data on the expansion and shrinkage due to moisture changes of Florida concrete are also lacking.

In view of the aforementioned reasons, this research project was started in order to obtain the needed data to be used in modelling and analysis of concrete pavement response and performance. In the course of this investigation, a need also arose in the determination of the coefficient of linear thermal expansion of structural concretes (Classes II, III & IV) used in Florida. The scope of the study was thus extended to cover the Florida Class II, III and IV concrete in addition to the pavement concrete (Class I).

1.2 Objectives of the Study

The main objectives of the study are

(1) To determine the coefficient of linear thermal expansion of Florida Class I, II, III and IV concrete.

(2) To determine the linear shrinkage and expansion due to moisture changes of Florida Class I, II, III and IV concrete.

(3) To determine the effects of mix parameters (such as aggregate type, water-cement ratio, and cement content) and curing time

on the coefficient of thermal expansion, and the shrinkage and expansion due to moisture changes of concrete.

(4) To determine the desirable concrete mixes to be used in concrete pavement construction.

CHAPTER 2
LITERATURE REVIEW

This chapter presents basic information on linear thermal expansion, definition of other thermal properties, a review of test methods previously used to determine linear thermal expansion of concrete, and the factors affecting the coefficient of linear thermal expansion of concrete.

2.1 Thermal Properties

The thermal properties of concrete which are of interest are coefficient of linear (and volumetric) expansion, thermal conductivity, thermal diffusivity, and specific heat [1].

2.1.1 Linear Thermal Expansion

Almost all solids expand as the temperature rises and contract as the temperature falls. Concrete is an example of a solid that expands or contracts due to the change in temperature. The change in length of a solid in response to the change in temperature is termed linear thermal expansion or contraction.

It is imperative to note that only uni-directional (or linear) expansion is considered even though we are fully aware of the area and volume expansion of solids due to change in temperature. The terms coefficient of linear thermal expansion and coefficient of thermal expansion are used interchangeably in this report.

According to Browne [2], the expansion of concrete due to increase in temperature is uniform over the range from 32 to 140 °F (0 to 60 °C). Mitchell [3:205] noted that the coefficient of thermal expansion is "essentially constant over the range from 15 to 70 °F (-9.46 to 21.1 °C) in dry concrete" whereas a moist concrete "frequently shows a significant increase in thermal coefficients with increasing temperature." The length of a concrete specimen as a linear function of the temperature is illustrated in Figure 2.1.

Let us consider a rectangular piece of concrete having a length, L_1 at temperature, T_1 (see Figure 2.2). If the temperature is increased from T_1 to T_2, the concrete will expand from L_1 to L_2.

Linear expansion is the name given to the change in length. The length change can be expressed as

$$\begin{aligned} \Delta L &= L_2 - L_1 \\ &= \alpha L_1 (T_2 - T_1) \\ &= \alpha L_1 \Delta T \qquad \text{Eq. 2.1} \end{aligned}$$

where

ΔL = change in the length

L_1 = original length at T_1

L_2 = final length at T_2

T_1 = original temperature

T_2 = final temperature

ΔT = change in temperature

α = coefficient of linear thermal expansion

It can be seen from Equation 2.1 that the change in length is proportional to both the original length, L_1 and the change in temperature,

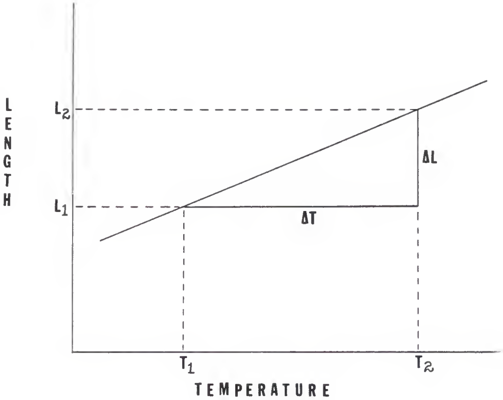

Figure 2.1 Uniform Expansion of Concrete

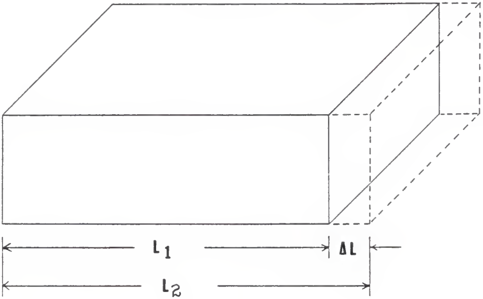

Figure 2.2 Linear Expansion of Solid

ΔT. The constant of proportionality is the coefficient of linear thermal expansion.

A positive change in length will increase the final length and conversely a negative change will result in the final length being shorter than the original. That is, the change in length can be additive or subtractive. Most engineering materials such as concrete can have a substantial change in length.

The coefficient of linear thermal expansion of concrete, denoted by α, is the change in the unit length per degree change in temperature. It is expressed in terms of millionths per degree centigrade ($\times 10^{-6}/°C$) or millionths per degree Fahrenheit ($\times 10^{-6}/°F$) or percent.

The coefficient of linear thermal expansion consists of the true thermal expansion and the apparent thermal expansion [3, 4]. The true or actual thermal expansion depends on the Kinetic molecular movements. Materials are composed of molecules which are in constant motion caused by forces of intermolecular attraction and repulsion. As the temperature increases, the molecular movement is also increased resulting in an expansion of a material. The expansion caused by molecular movement is constant.

The apparent thermal expansion is caused by "adsorptive mass attraction forces and capillary stresses" [5:67]. It is also termed "swelling pressure" [4:493]. This type of expansion occurs in the cement paste region of the concrete. About 25% to 40% of the total volume of concrete is made up of cement paste [6]. The cement paste is hygroscopic. In the presence of free (evaporable) water, adsorptive and capillary forces are developed. The magnitude of the forces depends on the change in temperature. As the temperature increases, the surface tension of the water and the capillary tension are reduced. Swelling pressure, which Dettling [5:17] defined as the "outer pressure needed to prevent swelling when a non-water-saturated gel has access to free water," is lost enabling the gel to withdraw water from the capillaries until equilibrium is once more attained. The cement paste swells when the cement gel gains water and shrinks when water is lost. Therefore, as the temperature rises at constant water content, the solid phase swells (apparent thermal expansion) in addition to the actual or true thermal expansion [7]. Moisture content, capillary structure of hardened cement paste, and quantity and expansion properties of cement gels are some factors that affect the magnitude of the apparent thermal expansion. According to Meyers [8], the apparent thermal coefficient of neat hardened cement paste is at minimum when completely water-saturated, a condition when all pores and capillaries are filled with water (100% saturated) and when all the evaporable water is removed, i.e., "bone dry" (0% evaporable water). Powers and Brownyard [7] attributed the condition to the existence of equality between vapor pressure of capillary water and saturation pressure of water at the existing temperature. A maximum value for the apparent thermal expansion of hardened cement paste and capillary forces is reached at a moisture content of about 70% of saturation [8]. Apparently capillary tension increases as water is lost from a water-saturated (100% saturation) specimen and also when moisture content is increased in a dry (0% moisture content) specimen.

The coefficient of volumetric thermal expansion is the ratio of the change of volume per unit volume per degree of temperature change. Volume change is expressed as

$$V_t = V_o(1 + \beta t)$$

where

V_t = final volume at t temperature change

V_o = initial volume

β = coefficient of volumetric thermal expansion.

The coefficient of volumetric thermal expansion for an isotropic material is equal to three times the coefficient of linear thermal expansion; i.e.,

$$\beta = 3\alpha \quad .$$

2.1.2 Thermal Conductivity

It is the rate of heat flow, by conduction, through a body of unit thickness and unit area for a unit temperature difference between two surfaces. Thermal conductivity is expressed as

$$Q = \frac{K\ (t_2 - t_1)\ aT}{d}$$

where

Q = heat conducted, cal gm/cm-sec-deg C

K = specific heat conductivity, calories

t_2-t_1 = temperature difference, deg C

a = cross sectional area, cm^2

d = thickness, cm

T = elapsed time, sec.

2.1.3 Thermal Diffusivity

It is defined as the thermal conductivity of a substance divided by the product of its density and specific heat, that is,

$$a = \frac{k}{C\rho}$$

where

a = thermal diffusivity (diffusion constant), m^2/hr or ft^2/hr

k = thermal conductivity

C = specific heat

ρ = density

It represents the rate at which a body with nonuniform temperature approaches equilibrium. According to Fintel [9], the diffusivity of concrete increases with an increase in aggregate content or decrease in water-cement ratio, and it decreases with an increase in temperature of the concrete.

2.1.4 Specific Heat or Thermal Capacity

Specific heat represents the amount of heat required to raise the temperature of a unit mass of homogeneous material by one degree. It is expressed as follows:

$$S = \frac{H}{m\,(t_2 - t_1)}$$

where

S = specific heat

H = quantity of heat added

m = weight of material

$t_2 - t_1$ = temperature change in degrees

2.2 Test Methods

The absence of a standard method for determining the coefficient of linear thermal expansion of concrete has resulted in a situation where methods used by researchers are "almost as numerous as the number of laboratories" [3:209].

Berwanger and Sarkar [10] studied the effect of temperature and age on thermal expansion and modulus of elasticity of concrete in the Civil Engineering Department at the University of Ottawa, Canada. Thirty-five 3 x 4 x 12-inch concrete prisms were cured both saturated and air-dried in the laboratory and tested at 7, 28, 84 days and at one year for coefficient of linear thermal expansion under short-term steady state temperatures ranging from -100 to 150 °F (-73 to 66 °C). Materials used included Type I Portland cement, fine aggregates having a fineness modulus of 2.7 and contained 35% quartz, 29% carbonates, 23% feldspar, and 13% of amphibole, garnet, magnetite, mica and pyroxene. The coarse aggregate maximum size was 3/4 inch and consisted of 65% limestone, 25% feldspar, 5% quartz, and 3% mica. The water-cement ratios used ranged from 0.43 to 0.71. The strength of the concrete at 28 days varied between 4800 and 6340 psi. Optical extensometer telescope was used to measure the change in length of the concrete prisms. Transducers such as Direct Current Displacement Transformers (DCDT) were used to measure the deformations of some of the specimens and the aluminum deformation correction plates. Thermocouples were embedded in some of the wet- and dry-cured concrete prisms in order to measure the actual temperatures during testing. The following conclusions were arrived at

(1) At above freezing temperatures, the coefficient of linear thermal expansion increased with age for both dry- and wet-cured

specimens. However, for a given water-cement ratio, the dry-cured specimens increased more with age. Coefficient of linear thermal expansion increased with decreased water-cement ratio.

(2) At below freezing temperatures, it is essentially the same as for above freezing temperatures although the increase with age was greater.

In his article entitled "Thermal Movement of Concrete," Browne [2] of Materials Research Laboratory at Taylor Woodrow Construction, United Kingdom, advocated the use of 6-inch diameter cylinders or 6 x 6 x 12-inch prisms for the measurement of linear thermal expansion of concrete. The prisms, he stated, should be immersed in water for 28 days from casting and then heat cycled in a water bath. Thermal strains, he said, should be measured by a mechanical, electrical or optical strain measuring device with a known temperature correction factor.

The expansion and contraction of concrete and concrete roads was studied by Goldbeck and Jackson [11] of former Office of Public Roads and Rural Engineering. The purpose of the laboratory study was to determine the change in length of concrete produced by the drying out and absorption of water. The concrete specimens used measured 8 in x 8 in x 5 ft high. Two one-half inch square steel bars were cast 50 inches apart into the concrete to serve as gage length. Materials used in preparation of specimens composed of normal (Type I) Portland cement, Potomac River sand, and crushed gneiss or gravel. The sand was coarse, and clean. All concrete mixtures were proportioned by weight and hand mixed at dry and wet consistencies. The quantity of water used for the dry mixtures was about 8.5% of the weight of dry materials. Between 10 and 12% was used for the wet mixtures. An instrument designed and constructed in their laboratory was used to take readings. It consisted of a micrometer head reading to 0.0001 inch mounted at the end of a steel yoke. The yoke contained two steel rods measuring five-sixteenths of an inch in diameter bolted to two end crosspieces, one holding the micrometer and the other a flat-ended steel pin. Readings were taken with the flat-ended pin held in contact with the lower conical point of the specimen and the micrometer screwed down to make contact with the upper conical point. Two readings were obtained. The readings were then averaged to obtain expansion or contraction along the center line. To detect change in the measuring instrument due to wear or misuse, readings were taken several times on a steel gage bar hung from the specimen. Readings were corrected for any change in temperature. It was observed that contraction took place almost immediately due to drying out of the water after molding. After 1 week of age, the specimen contracted approximately from 0.01 to 0.03 per cent, or from 0.0001 to 0.0003 inch per inch of length. The contraction, he reported, was caused exclusively by change in moisture. The finding from testing specimens kept in water for a period of about six months and allowed to dry in warm, dry air of the laboratory showed that concrete maintained almost constant expansion of approximately 0.0001 inch or 0.01 per cent while moist.

In a study conducted by Matsumoto [12] at the Engineering Experiment Station of the University of Illinois, the effect of moisture content upon the expansion and contraction of plain and reinforced concrete was investigated. The materials used were "universal" Portland cement, well graded sand from Attica, Indiana, as fine aggregate, and also gravel from Attica as coarse aggregate. The specific gravity of the sand and gravel were 2.69 and 2.71, respectively. The concrete was hand mixed. The mix proportions were 1:1:2, 1:2:4, and 1:3:6. A batch of concrete was made for each concrete specimen. The specimens numbered thirty and measured 2 x 3 x 24 inches. Two steel plugs in the specimens formed a 20-inch gage line. Specimens were demolded one day after batching. Initial measurements of the length and weight were recorded and then stored in a damp room covered with double sheets of burlap which were kept wet. The instrument used in length measurement was a Berry Strain gage of 20-inch gage length with a steel bar immersed in water of known temperature as a standard. In an event of temperature change, measurements were corrected accordingly. Changes in weight were regarded as gains or losses in moisture content. The test results are shown in Table 2.1. It was observed that concrete expanded when wet and contracted when placed in dry air. Concrete with a richer mix absorbed more water and consequently expanded more than the lean mix.

Pence [13] of the School of Civil Engineering, Purdue University, studied the coefficient of linear thermal expansion of concrete between 1899 and 1901. The concrete specimen used measured 6 x 6 x 24 inches originally but later specimens were made cylindrical with 4-inche diameter and 36-inche length because of the great length of time required to heat the former. The method employed to determine the coefficient of linear thermal expansion was to subject the concrete specimen to a temperature change, and then to determine the increase in length, from which the coefficient of thermal expansion could be computed. A standard bar of steel or copper with known coefficient of linear thermal

Table 2.1 Change in Moisture Content and Corresponding Changes in Length as Reported by Matsumoto [11]

Concrete Mix Proportion	Kept in Wet Condition for 60 days		Kept in Air of Room for 58 Days		Dried in Oven at 150°F for 14 Days		Dried in Oven at 200°F for 15 Days	
	Gain of Moisture (%)	Expansion (%)	Loss of Moisture (%)	Contraction (%)	Loss of Moisture (%)	Contraction (%)	Loss of Moisture (%)	Contraction (%)
1:1:2	0.85	0.0091	0.68	0.0358	2.86	0.0673	3.33	0.0807
1:2:4	0.89	0.0055	1.25	0.0333	2.80	0.0605	2.82	0.0636
1:3:6	0.64	0.0019	1.91	0.0362	3.21	0.0576	3.17	0.0622

Note: Expansion and contraction are given in per cent of gage length.

expansion and the concrete specimen were both subjected to changes in temperature. The principle of the "optical lever" was used to determine the difference of expansion of the concrete and steel or copper bars. The correction applied to the known coefficient of the metal bar was computed from the difference in length. The coefficient of linear thermal expansion of gravel concrete, broken stone concrete, and limestone bar was reported respectively as $5.4 \times 10^{-6}/^{0}F$ ($9.7 \times 10^{-6}/^{0}C$), $5.5 \times 10^{-6}/^{0}F$ ($9.9 \times 10^{-6}/^{0}C$), and $5.6 \times 10^{-6}/^{0}F$ ($10.1 \times 10^{-6}/^{0}C$).

Saemann and Washa [14] both professors of Mechanics, University of Wisconsin, Madison, conducted tests using mortars and concretes. The test temperatures varied between -70 and 450°F (-56.7 and 232 °C). Three concrete batches were made. The properties of the concrete mixes are presented in Table 2.2. The sand and gravel used were obtained locally in Madison, Wisconsin. The sand was calcareous and siliceous while the gravel was predominantly calcareous. Kenlite, an expanded shale, was obtained from Kentucky Light Aggregates, Inc. Type I Portland cement was used. The concrete specimens measured 2 x 2 x 11 inches and were cast with end studs. The specimens were moist-cured at normal room temperature for 14 days, then stored in air at 70°F (21.1°C) and 50% relative humidity for 13 days, and then held at test temperature for 24 hours prior to testing. During testing, the specimens were wrapped in paper and coated with paraffin to prevent change in moisture. Change in length accompanying a change in temperature from 70 to 0°F (21.1 to -17.8°C) was obtained and the coefficient of linear thermal expansion

Table 2.2 Properties of Concrete Mixes Used by Saemann and Washa [14]

Mix No.	1	2	3
Aggregate	Sand & Gravel	Sand & Gravel	Kenlite
Proportions by Weight	1:2.00:3.50	1:4.35:5.40	1:2.72
W/C Ratio	0.48	0.84	0.81*
Specific Weight (wet), (16 per cu.ft.)	151.9	149.1	109.5
Slump (inches)	3	3	2

* Total W/C ratio.

computed. A dial gage was used to measure change in length. The coefficient of linear thermal expansion for mixes 1, 2, and 3 were 4.4 x 10^{-6}, 4.4 x 10^{-6}, and 3.9 x $10^{-6}/^{0}F$ (7.9 x 10^{-6}, 7.9 x 10^{-6}, and 7.0 x $10^{-6}/^{0}C$), respectively.

Cruz and Gillen [15] performed tests to determine the thermal expansion of Portland cement paste, mortar, and concrete at high temperatures at the Engineering Development Division of the Portland Cement Association. A blend of four commercially produced Type I Portland cements was used. Elgin, Illinois, sand was used in the two concrete batches investigated. It was composed of 60% carbonates (mostly dolomite) and 40% siliceous material by weight. Two types of coarse aggregate were gravel from Elgin, Illinois, and crushed dolomite rock from Elmhurst, Illinois. The Elgin gravel was made up of 88% carbonates (mostly dolomite) and 12% siliceous material by weight and rock from Elmhurst was about 95% dolomite. The maximum size of coarse aggregate was 3/4 inch. The mix proportions by weight were 1:2.70:2.98 for Elgin concrete and 1:2.70:3.05 for Elgin/dolomite concrete. The W/C ratio by weight was 0.42 and 0.43 for Elgin and Elgin/dolomite concrete, respectively. The cement content of the two mixes was 568 pounds per cubic yard each. Both mixes had an air content of 4.5%. Three prisms measuring 5 x 6 x 6 inches were used per mix. The prisms were cast and cured for 7 days in a 100% relative humidity fog room at 23°C (73.4°F), dried for 20 days in an atmosphere of 50% relative humidity and 23%, and tested at an age of 28 to 30 days. Cores of 0.5-inch diameter and 3-inch length were cut from the prisms and used for the test. The equipment used was a commercially manufactured dilatometer. It consisted of a cylindrical electric furnace with the capability to heat specimens to 1600 °F (871°C). Length changes were measured by the Linear Variable Differential Transformer (LVDT). The temperature of the specimen was measured by a thermocouple. All the measurements were continuously recorded on an X-Y plotter. It was observed that Portland cement paste contracted while mortars and concretes expanded with increasing temperature. The average coefficient of linear thermal expansion for Elgin sand and gravel concrete was 7 x 10^{-6}/°F (12.6 x 10^{-6}/°C) and 7.9 x 10^{-6}/°F (14.2 x 10^{-6}/°C) for dolomite rock.

In addition, optical lever has been used by Willis and De Reus [16] in determining the coefficient of thermal expansion of small concrete specimens. Extensometer frames have been used by the U.S. Bureau of Reclamation and described by Mitchell [17]. Optical interferometer method was used by Parsons and Johnson [18] of the National Bureau of Standards, Washington, D.C., to determine the thermal expansion of 137 specimens of aggregates at a temperature range of -4 to 140°F (-20 to 60 °C).

Bonnell and Harper [19] measured the coefficient of thermal expansion of different British aggregates and of concretes prepared from them with different cements, over the temperature range of 32 to 104°F (0 to 40°C). Six cylindrical test specimens were made from each mix. They were cured in one of the two curing conditions namely (1) air at 65% relative humidity (air storage) or (2) water. The change in length of the specimens was measured using an apparatus described by Bonnell and Watson [20]. Bonnell and Harper arrived at the following conclusions:

(1) Siliceous aggregates have the highest coefficients of thermal expansion; limestones have the lowest coefficients while igneous rocks have intermediate coefficients. The value for the

coefficient of thermal expansion for aggregates were found to range from 2.1 to 6.5 x 10^{-6} per °F (3.8 to 11.7 x 10^{-6} per °C).

(2) The coefficient of thermal expansion of concrete depends largely on the type of aggregate used in the mix. Concrete made with siliceous aggregates have the highest thermal expansion, those with limestone have the lowest, and those with igneous aggregates intermediate. The coefficient of concretes ranges from 3.4 to 7.3 x 10^{-6} per °F (6.1 to 13.1 x 10^{-6} per °C).

(3) The richer mixes tend to have slightly higher thermal expansion.

(4) The effect of age on the thermal expansion of concrete is only minor.

(5) The method of curing and water content have only a small effect on the thermal expansion.

2.3 Factors Affecting Coefficient of Thermal Expansion of Concrete

The coefficient of linear thermal expansion of concrete has been reported to be affected by the following factors [2, 21, 22]:

1. Type and amount of aggregate
2. Moisture content
3. Type and amount of cement
4. Concrete age

The first two factors are the principal factors affecting the coefficient of linear thermal expansion of concrete [2, 21].

2.3.1 Aggregate Type

In general, aggregates occupy about 60 to 80% of hardened concrete volume [2, 23, 6]. The coefficient of linear thermal expansion of concrete is largely dependent on the composition and quantity of the aggregates. Tables 2.3 and 2.4 show the reported average coefficients of linear thermal expansion of various rocks and minerals, respectively, within normal temperature ranges [5]. Quartz has the highest coefficient of linear thermal expansion of any common mineral. The coefficients of various types of rocks are directly related to their quartz content. Rocks such as quartzite, sandstone, and chert which are quartz-rich have the highest coefficients averaging about 6.7×10^{-6} per °F (12×10^{-6} per °C). Those with little or no quartz, such as limestone and marble have the lowest coefficients averaging approximately 2.8×10^{-6} per ^{0}F (5×10^{-6} per ^{0}C). Igneous rocks such as granite and basalt which have medium quartz content have intermediate values. The coefficient of linear thermal expansion of composite rocks may be determined from the proportions of the major minerals and their average expansion [1].

The pertinent aggregate thermal characteristics were summarized by Emmanuel and Hulsey [23] as follows:

1. Generally, thermal coefficients of expansion for aggregates are less than those for cement pastes.
2. Moisture content has little effect on the variability of the average coefficient for aggregates.
3. Siliceous rocks have the highest coefficient, carbonate rocks the lowest, and igneous rocks usually have intermediate values.

Table 2.3 Reported Coefficients of Linear Thermal Expansion of Various Rocks [5].

		Average coefficient of linear thermal expansion $10^{-6}/^{0}C$	
Type of Rock	Temp. range °C	Limit values	Average value
Quartzite, silica shale, flint, kieselgur, geyserite	0...60	11.0...12.5	11.8
Sandstones with siliceous binders	0...60	10.5...12.0	11.8
Other sandstones	0...60	10.0...12.5	11.0
Quartz sands and gravels	0...60	10.0...12.5	11.0
Clay shale	0...60	9.5...10.5	10.1
Mica shale Phyllite	0...60	10.0...11.0	10.7
Chlorite- and Talc- shale	0...60	7.0... 8.0	7.5
Granite, Arkosene, Quartz prophry, liparite Gneiss, Granulites	0...60	6.5... 8.5	7.4
Syenites, feldspathic porphyry, trachyte Diorites, porphyrite, Andesite, phonolite Gabbros, diabase, Basalt Peridotites, pikrite, Limburgit	0...60	5.5... 8.0	6.5
Dense, crystalline, porous or odlitic limestones, lime sinter	0...30	a)3.5... 6.0 b) c) to 11.0	4.5 -
a) pure Galcite b) with Aragonite c) with Admixtures	30...60	a)4.0... 6.5 b) c) to 11.5	5.0 -
Marbles	0...30 30...60	4.0... 7.0 6.0...10.0	4.5 6.5
Dolomites, Magnesites	0...60	7.0...10.0	8.5

Table 2.4 Reported Coefficients of Linear Thermal Expansion of a Few More Important Rock Minerals [5].

Type of Mineral	Average coefficient on linear expansion $10^{-6}/{}^{0}C$
Silica Group	
Quartz, Chalcedony	11.5 to 12
Opal	6 to 7
Feldspar Group	
Potassium feldspars	
Orthoclase) Microline)	6.5 to 7.5
Sodium calcium feldspars	
Albite (sodium feldspar)	5 to 6
Oligoclase) Andesite) Labrador) Bytownite)	4 to 3
Anorthite (calcium feldspar)	2.5 to 3
Feldspathoids	(ca. 4.5 to 7.5) 1)
Mica Group	ca. 8 to 12
Augite - and hornblende group	ca. 6.5 to 7.5
Olvine group	6 to 9) 1)
Carbonates	
Calcite	4.5 to 5
Aragonite	20.5

1) The values cannot be regarded as free from uncertainty, as they have not been checked by measurements.

4. Similar types of rocks from different sources have coefficients that correspond to their mineral compositions.
5. Limestone aggregates within a normal atmospheric temperature range have an average coefficient of approximately 2.5 x 10^{-6}/°F (4.5 x 10^{-6}/°C).

2.3.2 Moisture Content

The moisture content or the degree of saturation has been reported as one of the principal factors affecting the coefficient of linear thermal expansion of concrete. Neville [4, 24] reported that the effect of the moisture content on the coefficient of linear thermal expansion applies only to the paste component because thermal expansion is affected by (1) true kinetic thermal expansion and (2) swelling pressure. The true kinetic thermal expansion of a specimen is defined mainly by the spatial arrangement of its molecules and by the type of the material, and is not revealed by its chemical composition alone [5]. Swelling pressure is caused by a decrease in the capillary tension of water held by the paste with an increase in temperature [4, 24]. The variation of the coefficient of linear thermal expansion of cement paste is much greater than that of concrete [17].

Dry (0% saturation) concrete at a temperature range of 15 to 70°F (-9.4 to 21.1 °C) has an essentially constant coefficient of linear thermal expansion while moist or nearly saturated concrete shows a significant increase in coefficient with increase in temperature [3]. The coefficient of thermal expansion of partially saturated concrete is generally 1.1 x 10^{-6}/°F (2 x 10^{-6}/°C) greater than when saturated [2]. Browne [2] attributed the high partially saturated value to the increasing absorption by the gel of the capillary-held water with increasing temperature.

Dettling [5] is of the view that for rocks, the variation of degree of saturation has no effect on the value of the coefficient of linear thermal expansion of rocks but has some effects on that of concrete.

Dettling [5] regarded linear thermal expansion of concrete as a very complex physical process. The total linear thermal expansion is made up of (1) the actual linear thermal expansion and (2) the apparent linear thermal expansion [5]. The actual linear thermal expansion is the true linear thermal expansion caused by Brownian molecular movements produced by a change in temperature. Its value is constant. The apparent linear thermal expansion is a swelling pressure caused by "adsorptive mass attraction forces and capillary stresses" [5:67]. The swelling and shrinkage occur in the cement gels region because of internal moisture movements caused by a change in the capillary forces produced by variation in temperature [5]. A completely dry or fully water saturated specimen has no apparent linear thermal expansion. Hence maximum apparent thermal expansion occurs when the specimen is partially saturated. The value of apparent thermal expansion is variable since it depends on age and degree of saturation. Aging of cement gels with time will reduce apparent thermal expansion.

Orchard [25] pointed out that the coefficient of linear thermal expansion is not affected by drying wet-cured concrete specimens.

2.3.3 Type and Amount of Cement

The type of cement does not greatly affect the coefficient of linear thermal expansion of concrete, as reported by Orchard [25]. During the early age of concrete, Meyers [26] observed that the value of the coefficient is dependent on the quantity of tricalcium silicate (C_3S) in the cement. He observed that cement with a high amount of tricalcium silicate compound had a high coefficient and those with low tricalcium silicate had a low volume change with temperature variation. With time, cements with a low amount of tricalcium silicate appeared to have a coefficient in the same range as those with high tricalcium silicate [26].

The coefficient of linear thermal expansion was reported to increase with an increase in the cement content of the concrete mix [26].

2.3.4 Concrete Age

Aging of saturated specimens tends to reduce the coefficient of linear thermal expansion because of increased crystallization of the gel structure [2]. Neville [4, 24] attributed the increase in the amount of crystalline material in hardened paste to a reduction in the potential swelling pressure.

Orchard [25] pointed out that the time of wet-curing (i.e. in water) has little effect on the coefficient of thermal expansion, while the time of dry-curing (i.e. in air) has little effect up to 3 months and tends to reduce the coefficient of thermal expansion slightly between 3 months and 1 year.

Matsumoto [12] found that the coefficient of expansion of mortar and concrete for different proportions and ages is practically the same as far as the same materials are used in all mixtures.

2.3.5 Other Factors

2.3.5.1 Curing condition. The coefficient of linear thermal expansion of concrete was reported to be slightly higher when cured under dry conditions than wet conditions. Orchard [25] warned that the evidence was a little conflicting.

2.3.5.2 Heating/Cooling. According to Dettling [5], the coefficient of linear thermal expansion is higher during cooling than during heating. He reasoned that increased expansion during cooling is possible only when there is no plastic deformations and losening of structure.

Mitchell [17] and other investigators reported that the value of the coefficient for aggregate obtained by going from low to high temperature is frequently slightly higher than starting from high to low temperature

2.3.5.3 Air voids. The coefficient of linear thermal expansion of concrete was reported not to be affected by the presence of air voids [5, 24].

2.3.5.4 Size of test specimens. The determination of the coefficient of linear thermal expansion involves the measurement of very small changes in length. The accuracy and precision of the determination were reported to be greater for the longer specimens [27].

2.3.5.5 Type of storage liquid. The type of liquid used to store test specimens can affect the value of coefficient of linear thermal expansion. Meyers [26] noted that storage of test specimens at constant temperature in kerosene or glycerol does not cause the specimens to expand or contract as storage in water does. He reasoned that kerosene or glycerol does not become an integral part of the cement gel structure as water does.

2.3.5.6 Freezing temperature. Dettling [5] warned against the use of temperature range that includes 32 °F (0°C) to determine the coefficient of linear thermal expansion because freezing of pore water will cause volume change rendering the results inaccurate.

2.4 Effects of Thermal Expansion on Pavements

The property of concrete to contract and expand due to temperature and moisture variation is of tremendous importance to the engineers who design concrete structures. This dimensional instability influences the ability of concrete structures to provide maintenance-free service condition. Expansion and contraction affect concrete pavements in two ways. First, the existence of temperature and moisture differential between the top and bottom surfaces of the concrete pavement causes it to curl and warp, respectively [28]. Warping is counteracted by the weight of the slab [29]. Secondly, the expansion and contraction due to uniform temperature change in the entire cross section of the concrete pavement will result in the development of forces of friction between the pavement and the subgrade [29]. In addition to tensile stresses caused by wheel loads, a temperature drop also causes tensile stresses in concrete pavements. Conversely, a rise in temperature will produce compressive stresses. According to Bergstrom [29], the presence of compressive stresses in the boundary surface of pavement and subgrade can lead to blow-up unless the expansion joints are spaced not far apart.

CHAPTER 3
DEVELOPMENT OF A LABORATORY TESTING PROCEDURE FOR MEASURING LENGTH CHANGE OF CONCRETE

This chapter describes the development of laboratory testing procedure used to measure the change in length of concrete specimens in this research project.

3.1 Introduction

There are many different methods for measuring the thermal expansion of solids. The methods may be classified as mechanical, electrical, optical, and X-ray. Examples of a mechanical method are dial gages and micrometer screws. Transducers, gages, tape transmitters are examples of electrical methods. Optical method examples are mirror arrangement, measurement microscope, and interference. The choice of the method to use depends on several factors including

1. Degree of accuracy and sensitivity
2. Automated or manual procedure
3. Properties of the material
4. Quantity of the material to be measured
5. Temperature range of the measurement
6. Type of information needed
7. Economy

All the methods used to measure change in length can be categorized as either relative or absolute [30]. A method is termed relative when the expansion of the material being determined is measured relative to the expansion of another material. When the expansion of the material being investigated is measured direclty, the method is known as absolute.

A dial gage was selected to be used in the investigation. The selection of the dial gage method was influenced largely by the expediency, availability of equipment, size and quantity of the test specimens, and suitable experimental procedure. The method was found to be adequate for the investigation after preliminary experiments using the dial gage.

3.2 Test Equipment

The equipment used to conduct change in length measurements comprises essentially of a length comparator, water tank, and forced draft oven.

3.2.1 Length Comparator

The length comparator (see Figure 3.1) used was manufactured by the Humboldt Manufacturing Company, Norridge, Chicago, Illinois. It consists of a sensitive dial micrometer mounted on a sturdy upright support that is attached to a solid triangular base. The dial micrometer is graduated to read to 0.0001 inch. The range of the scale is 0.4000 inch. The dial has one large and two small count hands with needle pointers. The scale may be rotated to set for zero at any indication of the large needle pointer where it can then be locked by a set screw. The two smaller count hands with needle pointers on the face of the large dial show the number of revolutions of the larger pointer. One of the count hands shows the reading in 0.010 inch and the other hand shows it in 0.100 inch.

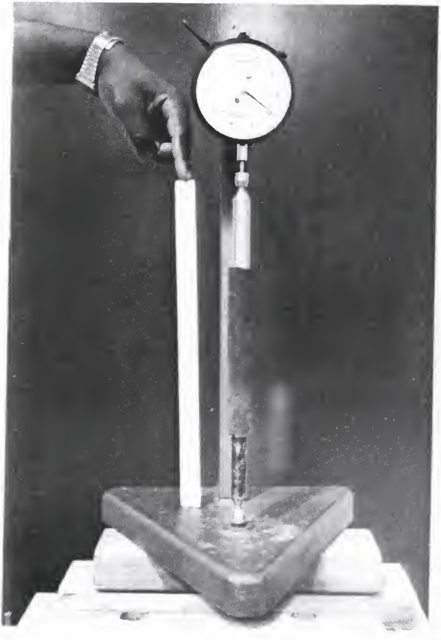

Figure 3.1 Length Comparator

There are two anvils fitted with collars and shaped to meet the measuring studs cast into the ends of the test concrete bars. As supplied by the manufacturer, one of the anvils is movable whereas the other is stationary. The movable anvil is attached to the end of the indicator spindle while the stationary anvil is attached to the base with a threaded fastener through the base and a hex lock nut. The original threaded fastener was replaced with a longer one to facilitate adjustment to various heights. This was necessary because the specimens obtained from in-service concrete pavements are approximately 9 inches while the laboratory specimens are 11.25 inches long.

3.2.2 Water Tank

A water tank which was to be used to saturate and condition the concrete specimens to specified test temperatures was constructed for this study.

The water tank is rectangular in shape measuring 4 feet long by 2 feet wide by 1 foot high (see Figure 3.2). It was fabricated in the laboratory from 0.125 inch steel.

The tank was fitted with a heating element, thermometer, thermostat, and a pump. The heating element is used to heat the water to the desired temperature. The water temperature is read from the thermometer while the thermostat is used to control the water temperature. The pump circulates the water in the tank. This is necessary to keep the temperature of the water uniform all over the tank.

The interior of the tank was cleaned and smoothened with sandpaper. It was sprayed with several coats of rust retardant and painted white. Two small hollow rectangular pieces of rods were glued to the

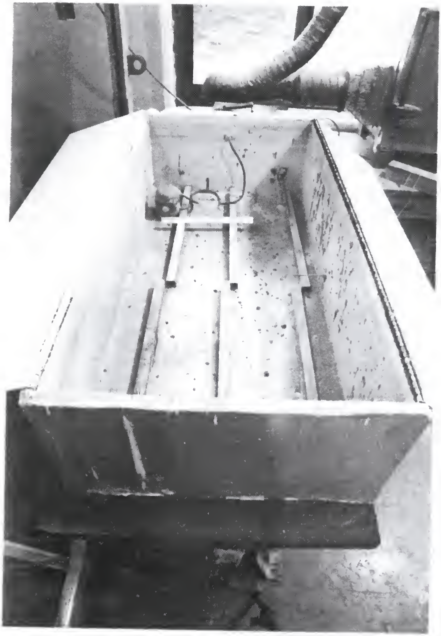

Figure 3.2 Water Tank

bottom of the tank for the specimens to be placed on. This helps to circulate the heated water to all surfaces of the specimens.

The exterior of the tank was insulated using Tuff-R Insulating Sheathing manufactured by the Celotex Corporation. It is a semi-rigid polyisocyanurate foam board insulation with a reinforced aluminum foil facer on one side and a solid aluminum foil facer on the other side. The nominal board thickness is 0.75 inch. The R-value, resistance to heat flow, at 75°F (23.9 °C) mean temperature aged over five years is 5.4.

3.2.3 Forced Draft Oven

A standard laboratory oven with approximately 2 cubic feet capacity was modified in the laboratory to enable flow of warm air through the oven. The modification was done by the provision of a large inlet port on one side of the oven and a small exit port on the top of the oven. A flexible aluminum duct was used to connect the two ports. A 375 cfm air booster was installed over the inlet port on the outside of the oven and connected to the duct line (see Figure 3.3.). A thermostat and sensor were also installed to control the temperature of the oven. A small hole was made on the side of the oven so that a thermometer could be inserted to check the temperature inside the oven.

3.2.4 Specimen Molds

A one compartment mold with inside dimension of 3 inches wide by 11.25 inches long was used to cast the test specimens. A total of ten molds were used per batch. The thickness of the steel mold is 0.5 inch. Two 0.375 inch thick, 3 inches square steel end plates with a hole at their centers were used to hold the contact points in place. Figure 3.4 shows a picture of the mold.

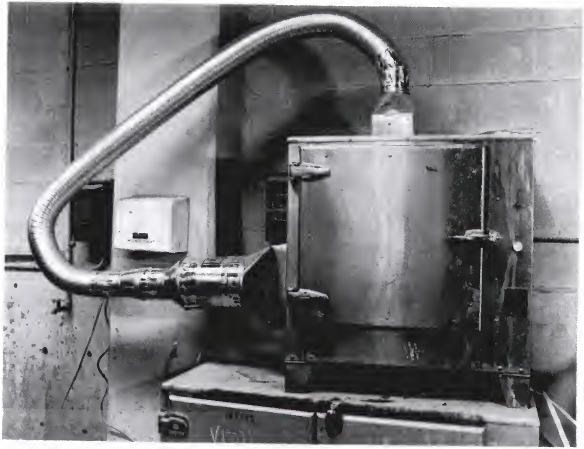

Figure 3.3 Forced Draft Oven

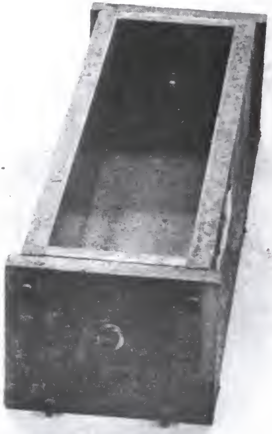

Figure 3.4 Specimen Mold

3.3 Test Specimens

Specimens used were either concrete bars batched in the laboratory or bars sawed from cores obtained from selected in-service concrete pavements. Coring of samples was done by the Florida Department of Transportation district crew and coordinated by the Materials Office, Gainesville. The core samples were delivered to the Civil Engineering Department for further preparation to the desired shape. The identified and rough dressed cylindrical cores measured approximately 6 inches in diameter by 9 inches long. The samples were machined in the laboratory to rectangular cross sections measuring approximately 3 inches wide by 3 inches thick by 9 inches long. Steel saw blades were used to cut the core samples to the desired dimension.

A hole was drilled on each of the two ends in the long direction. One end of the contact point was dipped in epoxy and firmly inserted into the hole. It was then left to harden. The amount of epoxy used is so small that it should not affect the result.

The laboratory specimens measured 3 inches wide by 3 inches thick by 11.25 inches long. The specimens were obtained from concrete batches with each batch varying from others in terms of W/C ratio, type of coarse aggregate used, and cement content. Figure 3.5 shows a picture of a concrete specimen with embedded thermocouples.

3.4 Test Procedures

3.4.1 Measurement of Length Change

Prior to measuring length changes of the specimens, a high and low reading for the standard invar reference bar was obtained. Another high

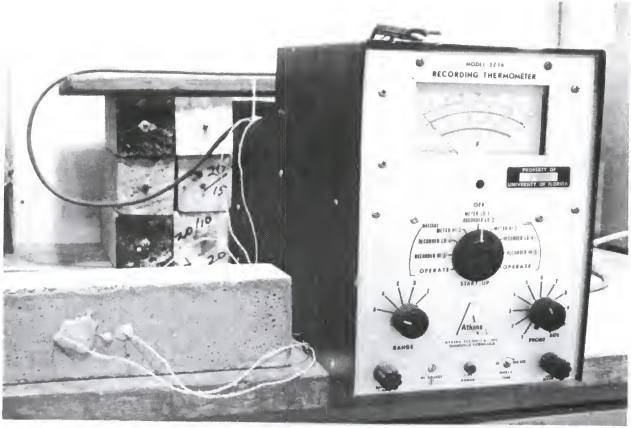

Figure 3.5 Concrete Specimen with Embedded Thermocouples

and low reference bar reading was taken at the conclusion of measurements at a particular temperature. This was done because the room temperature might not be constant at the location of the apparatus. This measurement is necessary in order to adjust for the change in length of the reference bar. The following formula was used to correct length readings of the reference bar, if necessary, taken at temperatures other than an arbitrary standard temperature:

$$L_{std.temp.} = L_X - (T_X - \text{Std.temp.})\, G\alpha \qquad \text{Eq. 3.1}$$

where

$L_{std.temp.}$ = corrected length reading of the reference bar,

L_X = length reading of the reference bar taken at temperature T_X,

G = gage length, and

α = coefficient of linear thermal expansion of the reference bar material.

The coefficient of linear thermal expansion of invar is $1.6 \times 10^{-6}/{}^{0}F$ ($0.9 \times 10^{-6}/{}^{0}C$) [31] and stainless steel value range from 5.5 to $9.6 \times 10^{-6}/{}^{0}F$ (9.9 to $17.3 \times 10^{-6}/{}^{0}C$) [32]. The reference bar for the laboratory specimens is an invar rod while that of field specimens is stainless steel.

The correction factor for a 5°F (2.8°C) variation in temperature is 0.000093 and 0.00026 for invar and stainless steel, respectively.

Specimens were initially conditioned to the desired temperature either in the oven or water tank for about 24 hours. The reason for this length of time is to make sure that the specimens actually attain the desired temperature. As the project progressed, specimen temperature was measured with thermocouples embedded at the surface and mid-depth (Figure 3.5). It was apparent from thermocouple readings that the desired temperature can be attained within 3 hours. Therefore, conditioning of specimens for 24 hours was abandoned. Readings were taken after at least 6 hours of conditioning.

A specimen was brought to the instrument with the dial indicator retracted. It was carefully positioned in the lower anvil and the indicator released very slowly and carefully to make contact with the upper anvil. The specimen was then rotated slowly while measurement of the length was read aloud by one person and recorded by another on each of the four sides. The use of two people to read and record the change in length of the specimens was necessary to prevent the specimens from cooling before readings were completed. At later readings, the use of a second person was abandoned as a cassette recorder was used instead. The mean of the four readings was used as the length reading for that cycle. It was found, as discussed in the next section, that using two cycles of reading was sufficient for the precision required for this study. Consequently, two cycles of readings were used. The direction of the rotation of the specimen in the length comparator for cycle 1 was opposite to that used for cycle 2. Two opposite directions were used to reduce the effects of the direction of rotation on the results. The specimens were placed in the length comparator with the same end pointed up each time a length measurement was made.

3.4.2 Determination of Degree of Saturation of Test Specimens.

The volume of permeable pore space or voids in the test specimen was determined in accordance with ASTM C 642-82 with minor modification to procedure 5.3. Since we are interested in knowing the moisture content of the specimen at the time of the test, the specimen was not allowed to "cool by natural loss of heat for not less than 14 hours to a final temperature of 68 to 77°F (20 to 25°C)" as required under the aforementioned procedure. Therefore, the saturated weight after boiling was obtained by weighing the surface-dried specimen after obtaining the change in length reading at 140°F (60°C).

The degree of saturation of watersaturated specimen was determine as follows:

Wt. of oven-dried specimen in air = A

Wt. of surface-dry specimen in air after immersion = B

Wt. of surface-dry specimen in air after immersion & boiling = C

Wt. of specimen in water after immersion & boiling = D

Since

$$\text{Voids (\%)} = \frac{C - A}{C - D} \times 100$$

$$\text{Degree of saturation} = \frac{V_w}{V_v} \times 100$$

$$= \frac{W_w}{\gamma_w V_v} \times 100$$

Therefore,

$$\text{Degree of Saturation} = \frac{C - A}{\gamma_w V_v} \times 100$$

where

γ_w = unit weight of water,

V_v = volume of voids

= volume of specimen x $\frac{\text{Voids(\%)}}{100}$.

3.4.2.1 Calculation of coefficient of linear thermal expansion The coefficient of linear thermal expansion, α of each of the samples was computed from the following equation:

$$\alpha = \frac{(L_2 - L_1)/L_1}{(T_2 - T_1)} \qquad \text{Eq. 3.1}$$

where

α = coefficient of linear thermal expansion,

L_1 = original length,

L_2 = final length,

T_1 = original temperature, and

T_2 = final temperature

3.4.3 Evaluation of the Test Method

A preliminary study was conducted to determine the effectiveness of the test procedure. First, the variability of the length readings from cycle to cycle was determined for various environmental conditions. Then, the number of cycles of readings was determined based on the variability of the data.

Table 3.1 displays the typical readings for four different conditions, namely (1) oven-dry at room temperature, (2) oven-dry at 140 °F, (3) saturated at room temperature, and (4) saturated at 140 °F. It can be noted that the variablility of readings from cycle to cycle (as seen from the standard deviation, S_x) is higher when readings are taken at 140 °F. For all the conditions, the standard deviations are equal or less than 0.0001 inch, which is the sensitivity of the length comparator. This indicates that the method used for the measurement of the

Table 3.1 Typical Length Readings for Four Different Environmental Conditions.

CYCLE	SIDE	OVEN-DRY 82.4 °F* (28 °C)	OVEN-DRY 140 °F (60 °C)	SATURATED 81.5 °F (27.5 °C)	SATURATED 140 °F (60 °C)
1	A	0.21112**	0.19659	0.22194	0.18490
	B	0.21110	0.19662	0.22194	0.18490
	C	0.21109	0.19662	0.22193	0.18489
	D	0.21109	0.19658	0.22192	0.18488
	AVG.	0.2111000	0.1966000	0.2219330	0.1848925
2	A	0.21100	0.19654	0.22194	0.18509
	B	0.21110	0.19656	0.22194	0.18500
	C	0.21104	0.19656	0.22192	0.18503
	D	0.21110	0.19655	0.22192	0.18504
	AVG.	0.21106	0.1965530	0.2219300	0.1850400
MEAN		0.2110800	0.1965765	0.2219315	0.1849663
STD. DEV.		0.0000283	0.0000332	0.0000021	0.00010
STD. DEV. of Mean (if 2 cycles are used)		0.0000200	0.0000235	0.0000015	0.0000738

NOTE: * Temperature of specimen at time of test.
** Length readings are relative and in units of inches.

length is fairly effective and its precision is limited only by the precision of the length comparator. Although it may be sufficient to use only one cycle of measurement, it is decided to use two cycles of measurement so that (1) the mean length measurement would be more reliable, and (2) the variability of the readings could be checked. Table 3.1 also displays the standard deviations of the mean length readings for two cycles. It can be seen that the standard deviations of the means are much less than 0.0001 inch.

The coefficient of linear thermal expansion, α of each of the samples was computed from the following equation:

$$\alpha = \frac{(L_2 - L_1)/L_1}{(T_2 - T_1)} \qquad \text{Eq. 3.2}$$

where

α = coefficient of linear thermal expansion,

L_1 = original length,

L_2 = final length,

T_1 = original temperature, and

T_2 = final temperature

The relationship for the coefficient of linear thermal expansion expressed in degree Fahrenheit and Centigrade is

$$\alpha/{}^0C = 1.8\ \alpha/{}^0F \qquad \text{Eq. 3.3}$$

CHAPTER 4
TESTING PROGRAM

This chapter presents the design of the experiment and the testing procedures used in the testing of laboratory and field specimens in this research study.

4.1 Laboratory Testing Program

4.1.1 Design of the Experiment

By the design of an experiment, we simply mean the plan of an experiment [33]. Experiments are planned or designed solely to provide the experimenter with maximum amount of information relevant to the problem being investigated at minimum cost. Also, analysis of data collected from designed experiment by statistical methods will yield valid and objective conclusions [33].

One of the main objectives of the laboratory study is to determine the effects of mix parameters (such as aggregate type, water-cement ratio, and cement content) and curing time on the coefficient of linear thermal expansion, and the shrinkage and expansion due to moisture changes of Florida Class I, II, III, & IV concrete.

To achieve this objective, an incomplete factorial experiment incorporating the following variables was used in the study:

1. Three aggregate types--Brooksville limestone, a river gravel, and a dense limestone (Calera aggregate).

2. Cement contents--508, 564, 658, and 752 lbs. per cubic yard.
3. Water/cement ratios--0.53, 0.45, 0.38, and 0.33.
4. Curing times--28 days and 3 months.

The concrete mixes for this study are displayed in Table 4.1. Two replicate batches per mix were made in order to have a reasonable statistical base. This amounts to a total of 24 batches. The order of making and testing the 24 batches was completely randomized.

A target slump of 3 inches was aimed for and was achieved by adding appropriate amounts of superplasticizer to the mixes. The exact proportioning of mix ingredients was determined from the trial batches. Initial designs of the trial batches were made using the COMIX computer program [34].

The tests performed on the hardened concrete specimens at the various curing conditions were (1) flexural strength test using simple beam with third-point loading to determine the modulus of rupture which is the maximum stress at rupture, (2) compression test to determine the compressive strength and static modulus of elasticity, (3) length change due to temperature and moisture test, and (4) splitting tensile test to determine the splitting tensile strength (see Table 4.2).

The following tests was conducted on the fresh concrete for each batch of concrete:

1. Slump test
2. Air content test
3. Unit weight test.

Table 4.1 Mix Combinations for the Laboratory Study.

Aggregate Type	Concrete Class	Cement Content (lb. per cu. yd.)			
		508	564	658	752
Brooksville Limestone	I w/c = .53	X	X		
	II w/c = .45		X	X	
	III w/c = .38			X	
	IV w/c = .33				X
River Gravel	I w/c = .53	X			
	II w/c = .45		X		
	IV w/c = .33				X
Dense Limestone	I w/c = 0.53	X			
	II w/c = .45		X		
	IV w/c = .33				X

Note: X Two replicate batches per cell

Table 4.2 Tests Performed on Each Batch of Concrete.

Curing	TEST			
	Flexural Strength (ASTM C78)	Compression (ASTM C469)	Length Change due to temperature and moisture	Splitting Tensile Test (4" x 8" cylinders)
28 days Moist Room	X	X	X	X
3 months Moist Room	X	X	X	X

Note: X Three replicate samples per cell.

4.1.2 Fabrication of Concrete Specimens

4.1.2.1 Mixing of concrete. The concrete batches were mixed in a stationary nontilting rotary type mixer with a maximum capacity of 25 cubic feet. The concretes was prepared in 13 cubic feet batches. The coarse aggregate and some mixing water was added into the mixer prior to starting rotation. A solution of air entrainment admixture was added to the mixing water. While the mixer was running, fine aggregate, cement, and about 80% of required water were added. After all the ingredients were in the mixer, the concrete was mixed for 3 minutes followed by a 3-minute rest. The remaining water was added to the mixer followed by a 2-minute final mixing. A slump test was run to determine whether or not a target slump of 3 inches has been reached. If the slump was too low, a water reducing admixture, Mighty RD-1, was added to the mixture followed by another 2-minute mixing. Another slump test was performed and the process as elucidated above repeated until the target slump was achieved. The amount of water reducing agent added to the concrete mix was small and so should not have any significant effect on the coefficient of linear thermal expansion.

4.1.2.2 Casting of concrete Specimens. After mixing was complete the concrete was discharged into a large hopper through a rectangular opening on the side of the mixer. Concrete was extracted as needed from the hopper for fresh concrete tests, and for casting of beams, cylinders, and test specimens. The following tests were performed on the fresh concrete: slump test (ASTM C143-78), air content test (ASTM C173-78), and unit weight test (ASTM C138-81) [35]. The concrete mixture was then placed in 6" x 12" plastic cylinder molds, 4" x 8" plastic cylinder molds, 6" x 6" x 30" steel beam molds, and 3" x 3" x 11-1/4" steel specimen molds. The molds were placed on two 20" x 20" syntron vibratory tables and vibrated while being filled with concrete mixture. Six 6" x 6" x 30" beam specimens, six 6" x 12" cylindrical specimens, six 4" x 8" cylindrical specimens, and ten 3" x 3" x 11-1/4" test specimens were cast for each batch of concrete. They were cured under a plastic sheet cover for about 20 to 24 hours before being demolded and cured in the moist room.

4.1.2.3 Curing of concrete specimens. The concrete specimens were cured under two conditions, namely, 28-day and 90-day moist curing.

The moist room conforms with the ASTM requirements that the relative humidity be greater than 98% and the temperature be at 73 ± 3°F (22.8 ± 1.6 °C).

4.1.3 Testing of Fresh Concrete

The tests performed on the fresh concrete are slump, air content, and unit weight.

4.1.3.1 Slump test. The slump test was performed in accordance with ASTM C143-78. Slump test is used to measure the consistency of concrete. The Florida Department of Transportation specified a slump range of 0 - 3.5 inches for vibrated placing of Class I, II, III, and IV concrete. For non-vibrated placing, FDOT specified a slump range of 0 - 6 inches, 3 - 5 inches, and 7 - 9 inches for Class I, II, and III concrete, respectively. No slump range is specified for non-vibrated Class IV concrete.

4.1.3.2 Air content test. Air content test was performed according to ASTM C173-78. The FDOT specifications require that all paving and structural concrete should contain from 3 to 6 % of entrained air.

4.1.3.3 Unit weight test. The unit weight test was performed as prescribed in ASTM C138-81. The test result is used to verify the computed density of the concrete mixes and for quality control.

4.1.4 Testing of Concrete Specimens

The tests performed on the hardened concrete specimens are flexural strength, compressive strength, splitting tensile strength, and length change due to temperature and moisture. The latter test has been described in Chapter 3. The description of the other tests follows.

4.1.4.1 Flexural strength test. The test was performed in accordance with the ASTM C78-84 [35]. Three 6" x 6" x 30" beam specimens were used per batch per curing condition.

If failure occurs within the middle third of the beam span length, the modulus of rupture was calculated as follows:

$$f_r = \frac{P\ell}{bd^2} \tag{4.1}$$

where

f_r = flexural strength or modulus of rupture, psi,

P = maximum applied load, lbf,

ℓ = span length, inches,

b = average width of specimen, inches,

d = average depth of specimen, inches.

The formula for calculating the modulus of rupture when failure occurs outside of the middle third of the span length by not greater than 5% of the span length is as follows:

$$f_r = \frac{3Pa}{bd^2} \tag{4.2}$$

where

a = average distance between line of fracture and the nearest support measured on the tension surface of the beam, inches.

Test results were discarded if failure occured outside the middle third of the span length by more than 5% of the span length.

The tensile strength of concrete is overestimated by 50 to 100 percent because the flexure formula assumes a linear stress-strain relationship in the concrete beam entire cross section [36]. Mehta [36] pointed out that flexural strength test is preferred for quality control of concrete used for highway and airport pavements where the concrete is loaded in bending.

4.1.4.2 Compressive strength test. Compressive strength tests were performed according to ASTM Standard Test Method C39-83b for Compressive Strength of Cylindrical Concrete Specimens. Three 6" x 12" cylindrical specimens per batch per curing condition were used for this test.

The moduli of elasticity of the concrete specimens were also determined at the conclusion of 28 and 90 days moist curing. A compressometer was used to measure the deformation of the cylindrical specimen as it was loaded in compression. The ASTM Standard Method C469-83 for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression was followed during this test. The deformation at 40 percent of the average ultimate compressive strength of two concrete specimens was used to calculate the modulus of elasticity.

Modulus of elasticity was computed as follows:

$$E = \frac{\text{Stress}}{\text{Strain}} \qquad (4.3)$$

where

E = Modulus of elasticity, psi

Stress = Load/Area

$$= \frac{\text{Load (lb)}}{9\ \pi}\text{, psi}$$

$$\text{Strain} = \frac{\text{Actual deflection (in.)}}{\text{Height of specimen (in.)}}$$

$$= \frac{1/2 \times \text{Measured deflection (in.)}}{6\ \text{(in.)}}$$

$$= \frac{\text{Measured deflection (in.)}}{12}\text{, in./in.}$$

Essentially, modulus of elasticity is the measure of resistance of the concrete specimen to deformation. It is used to determine the stresses induced by strains caused by environmental effects, to calculate the design stresses under a known load in simple elements, and to compute moments and deflections in complex structures [36].

Three methods are used to compute static modulus of elasticity and hence given rise to three moduli known as chord modulus, secant modulus, and tangent modulus.

The chord modulus is the slope of a line drawn from a point after correction for concavity to a point corresponding to 40 percent of the ultimate load. Mehta [36] recommends shifting the base line by 50 micro-strain (50 μ in./in.) to correct for the slight concavity at the beginning of the stress-strain curve. This method yields a lower modulus [37].

The secant modulus is the slope of a line drawn from the origin to a point on the curve corresponding to a 40 percent stress of the failure load. This method was used to compute modulus of elasticity.

The secant modulus of elasticity is used in design [37].

The tangent modulus is the slope of a line drawn tangent to the stress-strain curve at any point on the curve.

4.1.4.3 Splitting tensile strength test. The splitting tensile strength tests were performed in accordance with ASTM Standard Method C496-71 for Splitting Tensile Strength of Cylindrical Concrete Specimens. Three 4" x 8" cylindrical specimens were used for this test.

The splitting tensile strength of the specimen was calculated as follows:

$$f_t = \frac{2P}{\pi \ell d} \qquad (4.4)$$

where

f_t = splitting tensile strength, psi

P = maximum applied load, lbf

ℓ = length of cylinder, inches

d = diameter of cylinder, inches

4.2 Study of In-Service Concrete

Concrete samples from existing concrete pavements and structures in Florida were obtained to study the thermal and hygroscopic properties of the in-service concrete. Ten pavement (Class I concrete), one Class II, one Class III and one Class IV concrete projects were selected for this study. Ten core samples (6 inches diameter) were obtained from each of these thirteen projects. Of these ten samples, two were evaluated in the splitting tensile strength test, two were evaluated for their elastic moduli and compressive strengths and the other six were sawed into 3-inch square prisms. Holes were drilled at the two ends of the prismatic samples and contact points were inserted into the holes and glued to the sample with epoxy. These prismatic bars were conditioned to various temperature and moisture conditions and the length changes were measured at these conditions using the procedure described in Chapter 3. The following temperature and moisture levels were used:

1. 77, 86, 104, 122, and 140 °F (25, 30, 40, 50, and 60°C) at oven-dry condition.
2. 77, 86, 104, 122, and 140 °F (25, 30, 40, 50, and 60°C) at saturated condition.
3. 77°F (25°C) at three different partially saturated conditions.

The conditioning procedure is similar to the laboratory specimen.

CHAPTER 5
MATERIALS

This chapter presents the properties of the Portland cements, aggregates, and admixtures used in the preparation of laboratory test specimens of this project.

5.1 Cements

The cement used was a Type II Portland cement manufactured by General Portland, Inc., Tampa, Florida. The results of physical and chemical analyses on the cement was supplied by the manufacturer and are listed in Tables 5.1 and 5.2.

5.2 Aggregates

Three types of coarse aggregate were used. They are a porous limestone (Brooksville aggregate), a dense limestone (Calera aggregate) and a river gravel. One maximum aggregate size of 3/8 inch (#89) was used. Tests on these aggregates were performed for another research study by Tia et al. [38]. Test results from that study were used. The physical properties of the coarse aggregates are displayed in Table 5.3. The gradation charts for the Brooksville, river gravel, and Calera aggregates are shown in Figures 5.1 through 5.3, respectively.

Table 5.1 Results of Physical Tests on Cement Used [38].

		TYPE II CEMENT
Fineness by Blaine air permeability test, cm^2/g		3970
Soundness (autoclave expansion), %		-0.01
Time of setting (Gilmore):	Initial, hrs:mins	2:45
	Final, hrs:mins	4:25
Compressive Strength:	1 Day, psi	1990
	3 Days, psi	3040
	7 Days, psi	4190
Air Entrainment, %		9.1

Table 5.2 Results of Chemical Analyses on Cement Used [38].

		CEMENT TYPE II
Silicon Dioxide (S_iO_2),	%	21.6
Aluminum Oxide (Al_2O_3),	%	4.5
Ferric Oxide (Fe_2O_3),	%	4.1
Magnesium Oxide (M_gO),	%	0.6
Sulfur Trioxide (SO_3),	%	2.9
Loss on Ignition,	%	0.9
Insoluble Residue,	%	0.17
Alkalis ($\%Na_2O+0.658K_2O$),	%	0.36
Tricalcium Silicate,	%	54
Dicalcium Silicate,	%	21
Tricalcium Aluminate,	%	4.8
Tetracalcium Alumino Ferrite,	%	12.6

Table 5.3 Physical Properties of Coarse Aggregates.

	Coarse Aggregate		
Property	Brooksville #89	Calera #89	River Grave #89
Bulk Specific Gravity (SSD)	2.50 (2.29)*	2.70	2.59
Absorption (%)	2.95 (5.34)*	0.4	1.46
Unit Weight (lb/ft^3)	92.0 (86.42)*	96.82	100.38

* Batches 9-12

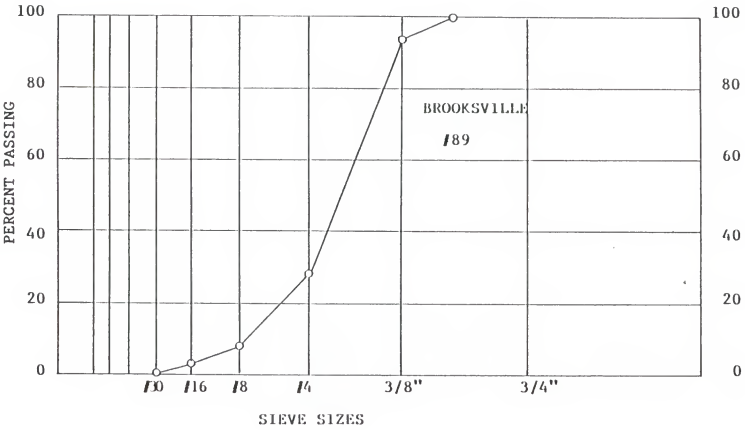

Figure 5.1 Gradation Chart for Brooksville Limestone #89 Coarse Aggregate Used in Batches 1-12 [38]

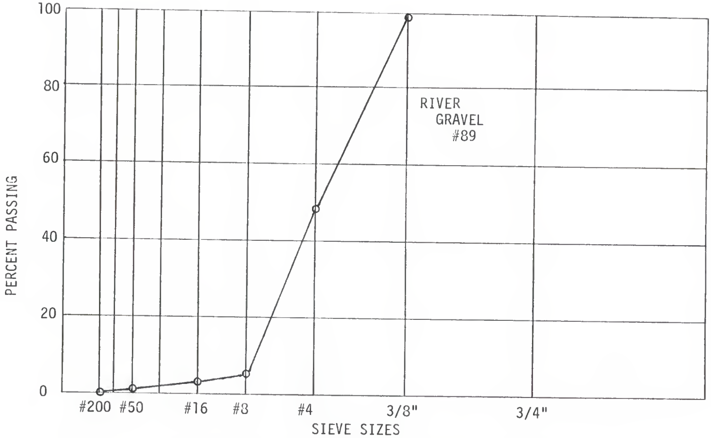

Figure 5.2 Gradation Chart for River Gravel #89 Coarse Aggregate Used in Batches 13-18

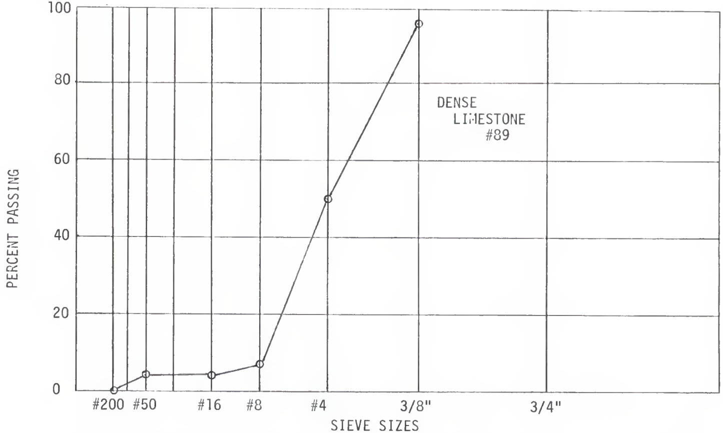

Figure 5.3 Gradation Chart for Dense Limestone #89 (Calera) Coarse Aggregate Used in Batches 19-24

The fine aggregate used for all mixtures was a fine sand from Goldhead, Florida. The gradation of this sand is depicted in Figures 5.4 and 5.5. The physical properties of this sand are as follows:

Bulk specific gravity (SSD) : 2.52 for batches 1-19
2.43 for batches 20-24
Absorption : 0.70% for batches 1-19
0.44% for batches 20-24
Fineness modulus : 2.26 for batches 1-19
2.11 for batches 20-24

5.3 Admixtures

An admixture, Mighty RD-1, was used to adjust the slump of the fresh concrete to a target slump of 3 inches. This admixture meets the requirements of ASTM C494 Type G and Type D, and is classified as a water-reducer and retarder.

A Darex air entraining admixture was used.

5.4 Epoxy

A Sikadur 32, Hi-Mod, 2-component (A & B), solvent-free moisture-insensitive structural epoxy adhesive was used to secure contact points to the field and some laboratory specimens.

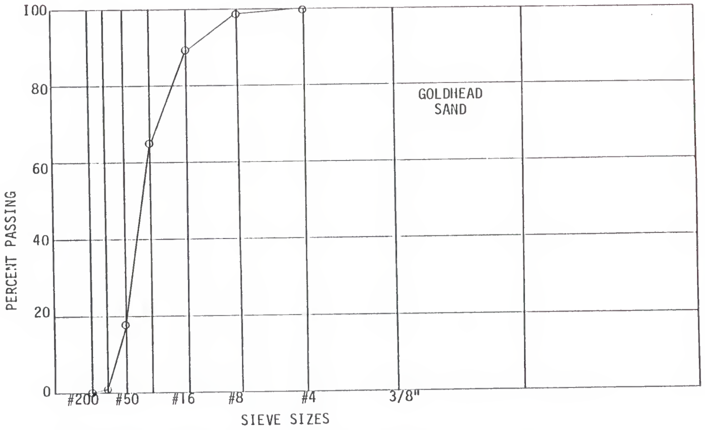

Figure 5.4 Gradation Chart for Goldhead Sand Used in Batches 1-19

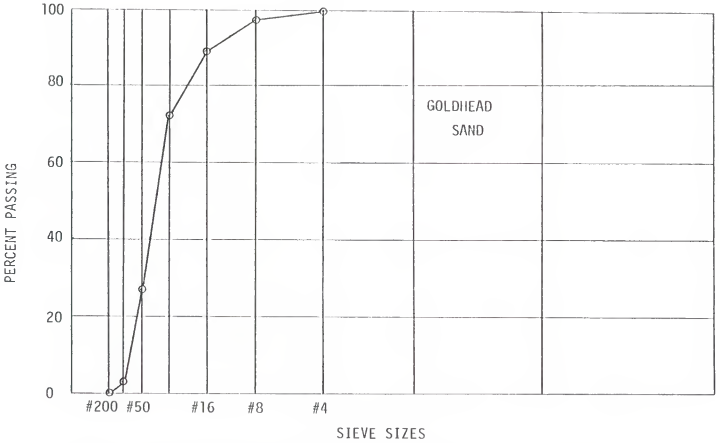

Figure 5.5 Gradation Chart for Goldhead Sand Used in Batches 20-24

CHAPTER 6
EXPERIMENTAL DESIGNS OF THE LABORATORY STUDY

6.1 Introduction

One of the principal objectives of this study as stated in Chapter 2 is to determine the effects of mix parameters (aggregate type, water-cement ratio, and cement content) and curing time on the coefficient of linear thermal expansion of concrete. In addition, the effects of mix parameters and curing time on the compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity will be studied.

The mix parameters (main factors) and their interactions are displayed in Table 6.1.

Table 4.1 summarizes the mix combinations for the laboratory study. Since the study involves more than one factor, a factorial experiment was used. A factorial experiment is referred to as complete if combination of all levels of each factor with all levels of every other factor exists. However, certain impractical factor level combinations (treatment combinations) were excluded from the study resulting in an incomplete factorial experiment. Statistical analysis and interpretation problems are created when some combinations are missing. In this study, a complete factorial experiment was precluded because of the specification requirement that a certain class of concrete must be made with a certain amount of cement and water-cement ratio. Treatment combinations

Table 6.1 Factors, Levels, and Interactions for the Partial Factorial Experiment.

Main Factors	Levels			
	1	2	3	4
Aggregate Type (A)	BL	RG	DL	
Cement Content - lb/cy (C)	508	564	658	752
Curing Duration - days (D)	28	90		
Water-Cement Ratio (E)	0.53	0.45	0.38	0.33

Two-Factor Interactions

A x C
A x D
A x E
C x D
C x E
D x E

Three-Factor Interactions

A x C x D
A x C x E
C x D x E

Four-Factor Interactions

A x C x D x E

NOTE:

BL = Brooksville Limestone
RG = River Gravel
DL = Dense Limestone

beyond the code stipulated limits would produce a concrete mix unsuitable for construction use.

In order that we can effectively analyze the significance of the main effects and interactions, the partial factorial design as shown in Table 4.1 is treated as seven (7) small complete factorial experiments. These seven experimental designs are described in this chapter.

6.2 Design No. 1

The purpose of this design was to study the effects of aggregate type, water-cement ratio, and curing duration on the dependent variables which are compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, and the coefficient of linear thermal expansion of the laboratory study. This design disregards the difference in the cement content of the batches. The main factors and their levels under study are

Factor A: - Aggregate type
    Level 1. Brooksville limestone
    Level 2. River gravel
    Level 3. Dense limestone
Factor D: - Curing duration
    Level 1. 28-day
    Level 2. 90-day
Factor E: - Water-Cement ratio
    Level 1. 0.53
    Level 2. 0.45
    Level 3. 0.33

Table 6.2 displays the experimental design. Each batch is replicated twice.

6.3 Design No. 2

At a fixed cement content of 508 lb. per cubic yard and water-cement ratio of 0.53, the effects of aggregate type (3 levels) and curing duration (2 levels) on dependent variables such as compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, and coefficient of linear thermal expansion are studied. The main factors and their levels are

Factor A: - Aggregate type
    Level 1. Brooksville limestone
    Level 2. River gravel
    Level 3. Dense limestone
Factor D: - Curing duration
    Level 1. 28-day
    Level 2. 90-day

The experimental design is shown in Table 6.3. There are two replicate batches for each mix design.

6.4 Design No. 3

In this of experiment, the main factors are the same as in Design No. 2 with the exception that the fixed cement content and water-cement ratio are 564 lb/cu.yd. and 0.45, respectively. The design is presented in Table 6.4.

Table 6.2 Design for Test on Effects of Aggregate Type, W/C Ratio at Variable Cement Content, and Curing Duration (Design No. 1).

W/C	0.53		0.45		0.33	
Cement Content	508 lb/cy		564 lb/cy		752 lb/cy	
Curing Duration Aggregate	28-day	90-day	28-day	90-day	28-day	90-day
Brooksville Limestone	X	X	X	X	X	X
River Gravel	X	X	X	X	X	X
Dense Limestone	X	X	X	X	X	X

X = Two replicate batches per cell.

Table 6.3 Design for test on effects of aggregate type and curing duration at W/C of 0.53 and cement content of 508 lb/cy (Design No. 2).

Curing Duration / Aggregate Type	28-Day	90-Day
Brooksville Limestone	X	X
River Gravel	X	X
Dense Limestone	X	X

Note: X = Two replicate batches per cell.

Table 6.4 Design for test on effects of aggregate type and curing duration at W/C of 0.45 and cement content of 564 lb/cy (Design No. 3).

Curing Duration / Aggregate Type	28-Day	90-Day
Brooksville Limestone	X	X
River Gravel	X	X
Dense Limestone	X	X

Note: X = Two replicate batches per cell.

6.5 Design No. 4

Design No. 4 is similar to Design No. 2 except that the fixed cement content and water-cement ratio are respectively, 752 lb/cu.yd. and 0.33. Table 6.5 shows the experimental design.

6.6 Design No. 5

In this design, the effects of the cement content and curing duration on the compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, and coefficient of linear thermal expansion was studied at fixed water-cement ratio and aggregate type. The design is presented in Table 6.6. The factors and their levels are

Factor C: - Cement content
  Level 1. 508 lb/cu.yd.
  Level 2. 564 lb/cu.yd.
Factor D: - Curing duration
  Level 1. 28-day
  Level 2. 90-day

Each mix design was duplicated twice.

6.7 Design No. 6

This design is similar to that of No. 5 except for the difference that the water-cement ratio is fixed at 0.45. The design is given in Table 6.7.

Table 6.5 Design for test on effects of aggregate type and curing duration at W/C of 0.33 and cement conte of 752 lb/cy (Design No. 4).

Curing Duration Aggregate Type	28-Day	90-Day
Brooksville Limestone	X	X
River Gravel	X	X
Dense Limestone	X	X

Note: X = Two replicate batches per cell.

Table 6.6 Design for test on effects of cement content and curing duration given W/C of 0.53 and Brooksville limestone (Design No. 5).

Cement Content (lb/cy) \ Curing Duration	28-Day	90-Day
508	X	X
564	X	X

Note: X = Two replicate batches per cell.

Table 6.7 Design for test on effects of cement content and curing duration given W/C of 0.45 and Brooksville limestone (Design No. 6).

Cement Content (lb/cy) \ Curing Duration	28-Day	90-Day
564	X	X
658	X	X

Note: X = Two replicate batches per cell.

6.8 Design No. 7

Design No. 7 dealt with the effects of water-cement ratio and curing duration of Brooksville limestone at cement content of 658 lb/cu.yd. on the compressive strength, splitting tensile strength, modulus of ruptue, modulus of elasticity, and coefficient of linear thermal expansion. Table 6.8 displays the design. The main factors and their levels are

Factor D: - Curing duration

- Level 1. 28-day
- Level 2. 90-day

Factor E: - Water-cement ratio

- Level 1. 0.45
- Level 2. 0.38

There are two replicate batches per mix design.

Table 6.8 Design for Test on Effects of W/C Ratio and Curing Duration Given Brooksville Limestone and Cement Content of 658 lb/cy (Design No. 7).

Curing Duration W/C	28-Day	90-Day
0.45	X	X
0.38	X	X

Note: X = Two replicate batches per cell.

CHAPTER 7
COMPRESSIVE STRENGTH OF LABORATORY CONCRETE SPECIMENS

7.1 Introduction

The compressive strength of concrete is dependent on a myriad of factors, among which are water-cement ratio, aggregate, and curing duration. This chapter presents the compressive strength results and the results of statistical analyses performed. The analyses includes analysis of variance (ANOVA) and Duncan's multiple range test.

7.2 Experimental Results

Table 7.1 summarizes the results of the compressive strength test on hardened concrete for each of the experimental designs.

7.3 Analysis of Results

7.3.1 ANOVA Models

7.3.1.1 Design No. 1. The test results for Design No. 1, which the combined test results of Designs 2 through 4, as tabulated in Table 7.1 were analyzed as a full factorial experiment using the following linear model:

$$Y_{ijklm} = \mu + A_i + E_j + (AE)_{ij} + \beta_{(ij)k} + \delta_{(ijk)} + D_l + (AD)_{il} + + (ED)_{jl} + (AED)_{ijl} + (BD)_{(ij)kl} + \varepsilon_{(ijkl)m} \qquad (7.1)$$

i = 1,2,3; j = 1,2,3; k = 1,2; l = 1,2; m = 1,2,3

Table 7.1 Results of Compressive Strength Test on Hardened Concrete

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Compressive Strength (psi)							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
2	0.53	508	BL	1	3017	3374	3491	3294	3547	3632	4085	3755
(1a)				2	3639	3692	3753	3695	4598	4605	4612	4605
			RG	1	2985	3272	3760	3339	3526	3646	3982	3718
				2	3371	3399	3770	3513	3947	4067	4071	4028
			DL	1	3611	3912	4028	3850	3869	4050	4227	4049
				2	5227	5323	5390	5313	5433	5733	5786	5651
3	0.45	564	BL	1	5383	5535	5606	5508	5383	5508	5606	5499
(1b)				2	5535	5588	5825	5649	5447	6324	6561	6111
			RG	1	4888	5072	5132	5031	5468	5471	5609	5516
				2	5355	5415	5546	5439	5613	5744	5903	5753
			DL	1	6221	6617	6911	6583	6907	7226	7523	7219
				2	5945	6522	7074	6514	6663	6794	6847	6768
4	0.33	752	BL	1	7314	7318	7760	7464	7983	8251	8421	8218
(1c)				2	6730	6741	7003	6825	7197	7243	7282	7241
			RG	1	6713	7335	7378	7142	7438	8372	8428	8079
				2	6727	7074	7335	7045	7760	8074	8152	7995
			DL	1	[illegible]	8336	8867	8403	9077	9699	9808	9528
				2	[illegible]	[illegible]	8874	8507	9245	9599	9673	9506

Table 7.1 continued

Design No.	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Compressive Strength (psi)							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
5	0.53	508	BL	1	3017	3374	3491	3294	3547	3632	4085	3755
				2	3639	3692	3753	3695	4598	4605	4612	4605
		564		1	3537	3586	3668	3597	3745	3890	3972	3869
				2	4096	4449	4488	4344	4616	4891	4909	4805
6	0.45	564	BL	1	5383	5535	5606	5508	5383	5508	5606	5499
				2	5535	5588	5825	5649	5447	6324	6561	6111
		658		1	5535	5967	6034	5845	6324	6607	6967	6633
				2	5287	5719	5804	5603	6013	6048	6133	6065
7	0.45	658	BL	1	(SAME AS IN DESIGN NO. 6)							
				2								
	0.38			1	6373	7229	7247	6950	7084	7289	8202	7525
				2	6274	6568	6677	6506	6897	7332	7647	7292

* Design No. 1 data is the same as that for Designs 2-4 combined.

** BL = Brooksville Limestone; RG = River Gra DL = Dense Lime ne.

where

Y_{ijklm} = response variable of the m^{th} specimen of the l^{th} level of curing duration, k^{th} batch, j^{th} level of water-cement ratio, and i^{th} level of aggregate type.

μ = overall mean.

A_i = effect of the i^{th} level of aggregate type.

E_j = effect of the j^{th} level of water-cement ratio.

$(AE)_{ij}$ = effect of the interaction of the i^{th} aggregate type and the j^{th} water-cement ratio.

$B_{(ij)k}$ = effect of the k^{th} batch nested under the i^{th} aggregate type and j^{th} water-cement ratio.

$\delta_{(ijk)}$ = restriction error caused by subjecting samples from the same batch to various different curing conditions.

D_l = effect of the l^{th} curing duration.

$(AD)_{il}$ = effect of the interaction of the i^{th} aggregate type with the l^{th} curing duration.

$(ED)_{jl}$ = effect of the interaction of the j^{th} water-cement ratio with the l^{th} curing duration.

$(AED)_{ijl}$ = effect of the interaction of the l^{th} curing duration, j^{th} water-cement ratio, and i^{th} aggregate type.

$(BD)_{(ij)kl}$ = effect of the interaction of the l^{th} curing duration with the k^{th} batch.

$\varepsilon_{(ijkl)m}$ = effect of the m^{th} random error within the l^{th} curing duration, k^{th} batch, j^{th} water-cement ratio, and i^{th} aggregate type.

7.3.1.2 Design Nos. 2-4. ANOVAs were performed on the test results from Design Nos. 2 through 4 using the following linear model:

$$Y_{ijkl} = \mu + A_i + B_{(i)j} + \delta_{(ij)} + D_k$$

$$+ (AD)_{ik} + (BD)_{(i)jk} + \varepsilon_{(ijk)l} \qquad (7.2)$$

$i = 1,2,3;\ j = 1,2;\ k = 1,2;\ l = 1,2,3$

where

Y_{ijkl} = response variable of the l^{th} specimen of the k^{th} level of curing duration, i^{th} level of aggregate type, and j^{th} batch.

μ = overal mean.

A_i = effect of the i^{th} level of aggregate type.

$B_{(i)j}$ = effect of j^{th} batch nested under i^{th} level of aggregate type.

D_k = effect of the k^{th} curing duration.

$(AD)_{ik}$ = effect of the interaction of the i^{th} aggregate type and the k^{th} curing duration.

$(BD)_{(i)jk}$ = effect of the interaction of the j^{th} batch and the k^{th} curing duration.

$\delta_{(ij)}$ = restriction error due to the fact that samples from the same batch are subjected to various different curing conditions.

$\varepsilon_{(ijk)l}$ = effect of the l^{th} random error with the $(ijk)^{th}$ experimental unit, assumed NID (o, σ^2).

7.3.1.3 Design Nos. 5 & 6. The following statistical linear model was used for ANOVAs on the test results from designs 5 and 6:

$$Y_{ijkl} = \mu + C_i + B_{(i)j} + \delta_{(ij)} + D_k + CD_{ik} + BD_{(i)jk} + \varepsilon_{(ijk)l} \qquad (7.3)$$

$i = 1,2;\ j = 1,2;\ k = 1,2;\ l = 1,2,3$

where

Y_{ijkl} = response variable of the l^{th} specimen of the k^{th} level of curing duration, i^{th} level of cement content, and j^{th} batch.

μ = overall mean.

C_i = effect of the i^{th} level of cement content.

$B_{(i)j}$ = effect of the j^{th} batch nested under i^{th} level of ceme content.

D_k = effect of the k^{th} level of curing duration.

CD_{ik} = effect of the interaction of the i^{th} level of cement content and the k^{th} level of curing duration.

$BD_{(i)jk}$ = effect of the interaction of the j^{th} batch and the k^{th} level of curing duration.

$\delta_{(ij)}$ = $(ij)^{th}$ restriction error.

$\varepsilon_{(ijk)l}$ = random error.

7.3.1.4 Design No.7. The test results for this design, which studied the effects of water-cement ratio and curing duration given Brooksville limestone and cement content of 658 lb/cy, were analyzed as full factorial experiments using the following linear statistical model:

$$Y_{ijkl} = \mu + E_i + B_{(i)j} + \delta_{(ij)} + D_k + (ED)_{ik} + (BD)_{(i)jk} + \varepsilon_{(ijk)l} \qquad (7.4)$$

$i = 1,2;\ j = 1,2;\ k = 1,2;\ l = 1,2,3$

where

Y_{ijkl} = response variable of the l^{th} experimental specimen of the k^{th} curing duration, j^{th} batch, and i^{th} water-cement ratio.

μ = overall mean.

E_i = effect of the i^{th} water-cement ratio.

$B_{(i)j}$ = effect of the j^{th} batch of the i^{th} water-cement ratio.

$\delta_{(ij)}$ = restriction error.

D_k = effect of the k^{th} curing duration.

$(ED)_{ik}$ = effect of the interaction of the i^{th} water-cement ratio with the k^{th} curing duration.

$(BD)_{(i)jk}$ = effect of the interaction of the j^{th} batch with the k^{th} curing duration.

$\varepsilon_{(ijk)l}$ = effect of the l^{th} random error of the $(ijk)^{th}$ experimental unit.

7.3.2 Statistical Methods of Data Analysis

7.3.2.1 Analysis of variance. The response variables were analyzed by a statistical method termed Analysis of Variance (ANOVA). The method was developed and introduced in 1924 by an English statistician named Sir Ronald A. Fisher (1890-1962). One of the uses of the ANOVA method is to determine the significance of the effects of the controlled independent variables (or treatments) to the response variables.

The SAS/STAT software developed by the SAS Institute Inc. was used to perform the analyses.

Two commonly used general purpose procedures offered by the SAS System for analysis of variance are PROC ANOVA and PROC GLM. The acronym GLM stands for General Linear Models and PROC is a truncation of the word procedure. PROC ANOVA is used only for balanced or orthogonal designs while PROC GLM is used for balanced as well as unbalanced designs. For specialized types of analyses, procedures such as PROC NESTED and PROC VARCOMP can be used. A balanced design is one with an equal number of observations in each cell.

The analysis of variance procedure partitions the total variation among observations into components associated with a source of variation. The mean square (or variance) of a source of variation is divided by the variation among units treated alike (experimental error) to obtain an F statistic used to test the significance of the difference among the means for the particular source of variation.

To construct appropriate test statistics, the expected mean squares [EMS] must be determined. The expected mean square algorithm for Design

No. 1, Design Nos. 2-4, Design Nos. 5 & 6, and Design No. 7 are presented in Tables 7.2 through 7.5, respectively.

Anderson and McLean [39] discussed succinctly the determination of the expected mean square algorithm.

An important result of an ANOVA is the P-value. It is an indication of the probability of error of the statement that a factor has a significant effect on the measured parameter. A lower P-value for a factor means that such factor has a higher level of significance. Commonly used standard critical P-values are 0.05 and 0.01. Factors such as cost and importance of the experiment should be carefully considered prior to the decision as to which P-value is to be used. Such decision is made in advance of the calculations. A probability of error (α) level of 0.05 was used. A factor is considered to be significant if the P-value of the factor is equal to or less than 0.05. The term "significant" as used here means "beyond the likelihood of chance". If the hypothesis that an effect is not present is rejected, the effect is considered significant. It should be noted that a statistical significance may not necessarily mean a practical significance or importance.

Prior to performing analysis of variance, the data was screened visually by scanning and printing of the high and low values of the data. The purpose is to locate and remove outliers which are observations removed from others. The presence of outliers cause the data to depart from the basic assumptions of ANOVA which are normal distribution, equal variances, and independent random samples. An assumption of independence among observations is satisfied because measurements were taken in

Table 7.2 Expected Mean Square Algorithm for Design No. 1

Model: $Y_{ijklm} = \mu + A_i + E_j + (AE)_{ij} + B_{(ij)k} + \delta_{(ijk)} + D_l + (AD)_{il} + (ED)_{jl} + (AED)_{ijl} + (BD)_{(ij)kl} + \varepsilon_{(ijkl)m}$

No. of Levels	3	3	2	2	3	Expected Mean Square
Type of Treatment*	F	F	R	F	R	(EMS)
Source / Subscript	i	j	k	l	m	
A_i	0	3	2	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 36\sigma_A^2$
E_j	3	0	2	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 36\sigma_E^2$
AE_{ij}	0	0	2	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 12\sigma_{AE}^2$
$B_{(ij)k}$	1	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2$
$\delta_{(ijk)}$	1	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2$
D_l	3	3	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BC}^2 + 54\sigma_D^2$
AD_{il}	0	3	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BC}^2 + 18\sigma_{AD}$
ED_{jl}	3	0	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BC}^2 + 18\sigma_{EB}^2$
AED_{ijl}	0	0	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BC}^2 + 6\sigma_{AED}^2$
$(BD)_{(ij)kl}$	1	1	1	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BC}^2$
$\varepsilon_{(ijkl)m}$	1	1	1	1	1	σ_ε^2

* F = Fixed R = Rand.

Table 7.3 Expected Mean Square Algorithm for Design Nos. 2-4

Model: $Y_{ijkl} = \mu + A_i + B_{(i)j} + \delta_{(ij)} + D_k + (AD)_{ik} + (BD)_{(i)jk} + \varepsilon_{(ijk)l}$

No. of Levels	3	2	2	3	Expected Mean Square
Type of Treatment*	F	R	F	R	(EMS)
Source / Subscript	i	j	k	l	
A_i	0	2	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 12\sigma_A^2$
$B_{(i)j}$	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2$
$\delta_{(ij)}$	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2$
D_k	3	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2 + 18\sigma_D^2$
$(AD)_{ik}$	0	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2 + 6\sigma_{AD}^2$
$(BD)_{(i)jk}$	1	1	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2$
$\varepsilon_{(ijk)l}$	1	1	1	1	σ_ε^2

* F = Fixed R = Random

Table 7.4 Expected Mean Square Algorithm for Design Nos. 5 & 6

Model: $Y_{ijkl} = \mu + C_i + B_{(i)j} + \delta_{(ij)} + D_k + CD_{ik} + BD_{(i)jk} + \varepsilon_{(ijk)l}$

No. of Levels	2	2	2	3	Expected Mean Square (EMS)
Type of Treatment*	F	R	F	R	
Source / Subscript	i	j	k	l	
C_i	0	2	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 12\sigma_C^2$
$B_{(i)j}$	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2$
$\delta_{(ij)}$	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2$
D_k	2	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2 + 12\sigma_D^2$
CD_{ik}	0	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2 + 6\sigma_{CD}^2$
$BD_{(i)jk}$	1	1	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2$
$\varepsilon_{(ijk)l}$	1	1	1	1	σ_ε^2

* F = Fixed R = Random

Table 7.5 Expected Mean Square Algorithm for Design No. 7

Model: $Y_{ijkl} = \mu + E_i + B_{(i)j} + \delta_{(ij)} + D_k + (ED)_{ik} + (BD)_{(i)jk} + \varepsilon_{(ijk)l}$

No. of Levels	2	2	2	3	Expected Mean Square (EMS)
Type of Treatment*	F	R	F	R	
Subscript Source	i	j	k	l	
E_i	0	2	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 12\sigma_E^2$
$B_{(i)j}$	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2$
$\delta_{(ij)}$	1	1	2	3	$\sigma_\varepsilon^2 + 6\sigma_\delta^2$
D_k	2	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2 + 12\sigma_D^2$
$(ED)_{ik}$	0	2	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2 + 6\sigma_{ED}^2$
$(BD)_{(i)jk}$	1	1	0	3	$\sigma_\varepsilon^2 + 3\sigma_{BD}^2$
$\varepsilon_{(ijk)l}$	1	1	1	1	σ_ε^2

* F = Fixed R = Random

a random order. The randomization of testing order distributes more evenly effects of uncontrolled factors such as learning curve of the experimeter, physical changes in the equipment such as wear, to mention but just two.

Burr-Foster Q-test was used to check the assumption of homogeneity of variance [39]. If the calculated Q value is less than critical Q value at $\alpha = 0.01$ level, the hypothesis of homogeneity of variance is accepted. Conversely, if the homogeneity test is rejected at $\alpha = 0.001$ level, a suitable transformation of the data is made before running the analysis of variance. A transformation equalizes the variance regardless of the mean value. If ANOVA is performed on the transformed data, conclusions from the analysis of variance apply directly to the transformed populations. The results of the Burr-Foster Q-test indicated no deviations from the assumptions.

7.3.2.2 Duncan's multiple range test. The rejection of the null hypothesis after running ANOVA only tells us that at least one pair of group means are unequal. In order to determine specifically which pair or pairs of means are unequal, multiple comparison of means was performed. The Duncan's multiple range test was used in treatment means comparison. Although there are numerous tests for comparing pairs of treatment means, (e.g., Least Significant Difference, Newman-Keuls, Tukey's, to mention just a few), only Duncan's test was used because of its ability to detect differences between means when such differences occur in actuality. The Duncan's test was performed using SAS/STAT software at a significance level of 0.05.

The use of Duncan's multiple range test to compare the levels of one factor is only recommended when there is no interaction of the factor with another factor because of averaging over the levels of the second factor. When there is say A x B interaction, the levels of factor A was compared for each level of factor B and vice versa.

7.3.2.3 Regression analysis. The third and last statistical method used in the analysis of the test results is the regression analysis or curve fitting. The prime purpose of applying regression analysis to the test results is to develop a mathematical relationship between the dependent and independent variables, which can be used to predict the response variable.

7.3.3 Results of Experimental Design No.1

ANOVA using SAS/STAT software was performed on the test results from Design No. 1, which studied the effects of aggregate type, water-cement ratio, and curing duration on the compressive strength of the concrete. In this design, the cement content was assumed not to have any effect on the dependent variable. The results obtained are summarized in Table 7.6. A probability of error level of 0.05 was used. All the main effects are highly significant since their P-values are less than 0.01. Only the interaction of water-cement ratio with curing duration is significant.

A comparison of means of aggregate type, water-cement ratio, and curing duration was performed using Duncan's multiple range test at a significance of 0.05. The results are summarized in Tables 7.7 through 7.9.

Table 7.6 Results of ANOVA on Data from Compressive Strength Test in Design No. 1

Source of Variation	df	SS	MS	F	P
A	2	36014801	18007401	14.31	0.0016**
E	2	277920427	138960214	110.42	0.0001**
AE	4	1559522	389881	0.31	0.8644
B(A*E)	9	11326452	1258495	-	-
D	1	8541281	8541281	133.76	0.0001**
AD	2	54566	27283	0.43	0.6649
ED	2	1277740	638870	10.00	0.0052**
AED	4	658492	16423	2.58	0.1096
BD(A*E)	9	574709	63857	0.84	0.5840
ε	72	5488459	76229	-	-

R-Square = 0.984018

** Significant at $\alpha = 0.01$ level.

Table 7.7 Grouping of Aggregate Type by Means of Compressive Strength of Concrete from Duncan's Test [Design No. 1]

Alpha = 0.05 DF = 9 MSE = 1258495

Aggregate	Mean	Grouping*
Dense Limestone	6824.2	A
Brooksville Limestone	5655.3	B
River Gravel	5549.9	B

* Note: Means with the same letter are not significantly different.

Table 7.8 Grouping of Water-Cement Ratio by Means of Compressive Strength of Concrete from Duncan's Test [Design No. 1]

Duration = 28-day: Alpha = 0.05 DF = 9 MSE = 491897

Duration = 90-day: Alpha = 0.05 DF = 9 MSE = 830455

Moist Curing Duration	Water-Cement Ratio	Mean	Grouping*
28 - day	0.33	7564.4	A
	0.45	5787.2	B
	0.53	3834.1	C
90 - day	0.33	8427.9	A
	0.45	6144.3	B
	0.53	4300.9	C

* Note: Means with the same letter are not significantly different.

Table 7.9 Grouping of Curing Duration by Means of Compressive Strength of Concrete from Duncan's Test [Design No. 1]

W/C = 0.33: Alpha = 0.05 DF = 6 MSE = 348056

W/C = 0.45: Alpha = 0.05 DF = 6 MSE = 206202

W/C = 0.53: Alpha = 0.05 DF = 6 MSE = 1429268

W/C	Curing Duration	Mean	Grouping*
0.33	90-day	8427.9	A
	28-day	7564.4	B
0.45	90-day	6144.3	A
	28-day	5787.2	A
0.53	90-day	4300.9	A
	28-day	3834.1	A

* Note: Means with the same letter for a given W/C are not significantly different.

According to Table 7.7, which grouped aggregate type by means of compressive strength of concrete, Brooksville limestone and river gravel are not significantly different. However, both aggregates are significantly different from dense limestone.

Table 7.8 grouped water-cement ratio using compressive strength means. All three water-cement ratio are significantly different.

The two curing durations are significantly different from one another at the W/C ratio of 0.33, but are not significantly different at W/C ratios of 0.45 and 0.53, as presented in Table 7.9.

7.3.4 Results of Experimental Design No. 2

Table 7.10 displays the results of ANOVA on the compressive strength of the concrete in Design No. 2, which studied the effects of aggregate type and curing duration at a fixed W/C ratio of 0.53. The effect of the curing duration is significant while the effect of aggregate type is not significant. It is as expected that prolonged moist curing of concrete will give the concrete more time to hydrate and hence increase in strength will result.

A comparison of the effect of aggregate type on compressive strength was further examined by performing the Duncan's multiple range test. The Duncan's test results are summarized in Table 7.11. The effects of the three aggregates on the compressive strength are not significantly different.

7.3.5 Results of Experimental Design No. 3.

Table 7.12 displays the results of ANOVA on the test results from Design No. 3, which investigated the effects of aggregate type and curing duration at a fixed W/C ratio of 0.45. At this water-cement

Table 7.10 Results of ANOVA on Data from Compressive Strength Test in Design No. 2

Source of Variation	df	SS	MS	F	P
A	2	7774855	3887428	1.39	0.3741
B(A)	3	8395596	2798532	-	-
D	1	1960933	1960933	32.68	0.0106*
AD	2	263428	131714	2.20	0.2586
BD(A)	3	180013	60004	1.35	0.2817
ε	24	1066397	44433	-	-

R-Square = 0.945706

* Significant at $\alpha = 0.05$ level.

Table 7.11 Grouping of Aggregate Type by Means of Compressive Strength of Concrete from Duncan's Test [Design No. 2]

Alpha = 0.05 DF = 3 MSE = 2798532

Aggregate	Mean	Grouping*
Dense Limestone	4715.8	A
Brooksville Limestone	3837.1	A
River Gravel	3649.7	A

* Note: Means with the same letter are not significantly different.

Table 7.12 Results of ANOVA on Data From Compressive Strength Test in Design No. 3

Source of Variation	df	SS	MS	F	P
A	2	12063416	6031708	19.24	0.0194*
B(A)	3	940398	313466	-	-
D	1	1147398	1147398	11.60	0.0423*
AD	2	80131	40066	0.40	0.6987
BD(A)	3	296817	98939	1.20	0.3310
ε	24	1978931	82455	-	-

R-Square = 0.880116

* Significant at α = 0.05 level.

ratio, the effects of both the aggregate type and curing duration are significant while the interaction effects are not significant.

The Duncan's multiple range test was performed at a significance level of 0.05 using SAS/STAT software. The results of the Duncan's test are presented in Table 7.13. There is no significant difference between Brooksville limestone and river gravel. However, both Brooksville limestone and river gravel are significantly different from the dense limestone.

7.3.6 Results of Experimental Design No. 4

The ANOVA results for Design No. 4, which investigated the same two factors as Design Nos. 2 and 3 but at a fixed W/C ratio of 0.33, are presented in Table 7.14. Both the effects of aggregate type and curing duration are significant, while the interaction effects are not significant.

The Duncan's multiple range test was conducted to determine which pair or pairs of aggregate type means are unequal. Table 7.15 shows the results of the Duncan's test. The results concur with those of Design No. 3 that there is no significant difference between Brooksville limestone and river gravel which are significantly different from the dense limestone.

7.3.7 Results of Experimental Design No. 5

The results of ANOVA on the compressive strength of the concrete in Design No. 5, which examined the effects of cement content and curing duration at a fixed W/C ratio of 0.53, are summarized in Table 7.16. The results connote that the effect of curing duration is significant while the other factors are not.

Table 7.13 Grouping of Aggregate Type by Means of Compressive Strength of Concrete from Duncan's Test [Design No. 3]

Alpha = 0.05 DF = 3 MSE = 313466

Aggregate	Mean	Grouping*
Dense Limestone	6770.8	A
Brooksville Limestone	5691.8	B
River Gravel	5434.7	B

* Note: Means with the same letter are not significantly different.

Table 7.14 Results of ANOVA on Data from Compressive Strength Test in Design No. 4

Source of Variation	df	SS	MS	F	P
A	2	17736052	8868026	13.37	0.0321*
B(A)	3	1990458	663486	-	-
D	1	6710690	6710690	205.68	0.0007**
AD	2	369499	184749	5.66	0.0958
BD(A)	3	97879	32626	0.32	0.8104
ε	24	2443131	101797	-	-

R-Square = 0.916752

* Significant at α = 0.05 level.

** Significant at α = 0.01 level.

Table 7.15 Grouping of Aggregate Type by Means of Compressive Strength of Concrete from Duncan's Test [Design No. 4]

Alpha = 0.05   DF = 3   MSE = 663486

Aggregate	Mean	Grouping*
Dense Limestone	8986.0	A
Brooksville Limestone	7565.5	B
River Gravel	7436.9	B

* Note: Means with the same letter are not significantly different.

Table 7.16 Results of ANOVA on Data from Compressive Strength Test in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	602300	602300	0.37	0.6071
B(C)	2	3299801	1649900	-	-
D	1	1660056	1660056	18.61	0.0498*
CD	1	152642	152642	1.71	0.3210
BD(C)	2	178441	89221	2.99	0.0791
ε	16	478223	29889	-	-

R-Square = 0.924943

* Significant at $\alpha = 0.05$ level.

7.3.8 Results of Experimental Design No. 6

Table 7.17 displays the ANOVA results for Design No. 6, which dealt with the effects of cement content and curing duration at a fixed W/C ratio of 0.45. The finding that the effect of cement content is not significant is in agreement with that of Design No. 5. However, curing duration is not significant at 0.05 alpha level but is significant at the 0.10 level.

7.3.9 Results of Experimental Design No. 7

ANOVA was performed on test results of Design No. 7, which studied the effects of water-cement ratio and curing duration given Brooksville limestone and cement content of 658 lb/cy, using SAS/STAT software. The results of the ANOVA are summarized in Table 7.18.

7.3.10 Graphical Presentation of Means

The means of the compressive strength test results have already been presented in Table 7.1. The relationship of the water-cement ratio and moist curing duration on the concrete compressive strength for each of the aggregate types are depicted in Figures 7.1 through 7.3.

The aggregate type-compressive strength relationship for water-cement ratios 0.33, 0.45, and 0.53 are presented in Figures 7.4 through 7.6.

7.4 Summary of Findings

The main findings from the results of the compressive strength test are epitomized as follows:

1. The aggregate type has some effects on the compressive strength of hardened concrete. At W/C ratios of 0.33 and 0.45, Brooks-

Table 7.17 Results of ANOVA on Data from Compressive Strength Test in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	713115	713115	1.55	0.3387
B(C)	2	917332	458666	-	-
D	1	1085025	1085025	8.84	0.0970
CD	1	237805	237805	1.94	0.2986
BD(C)	2	245617	122809	1.51	0.2512
ε	16	1303148	81447	-	-

R-Square = 0.710543

Table 7.18 Results of ANOVA on Data from Compressive Strength Test in Design No. 7

Source of Variation	df	SS	MS	F	P
E	1	6387048	6387048	15.30	0.0596
B(E)	2	835145	417573	-	-
D	1	2553885	2553885	45.25	0.0214*
ED	1	4732	4732	0.08	0.7994
BD(E)	2	112887	56444	0.43	0.6570
ε	16	2093790	130862	-	-

R-Square = 0.825335

* Significant at $\alpha = 0.05$ level.

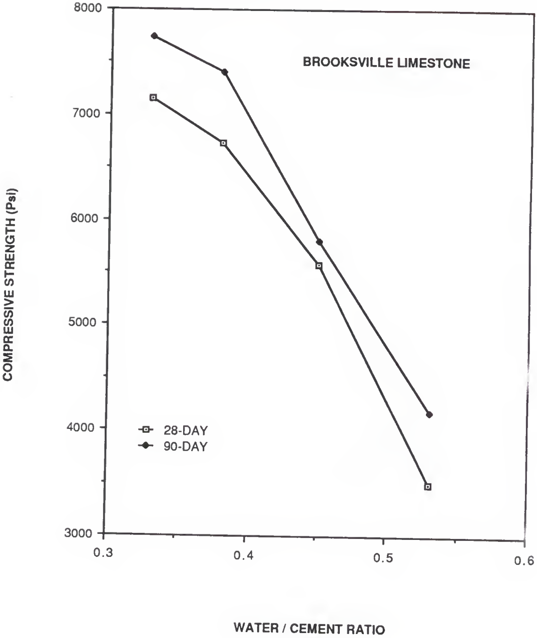

Figure 7.1 Influence of Water/Cement Ratio and Moist Curing Duration on Concrete Strength Using Brooksville Limestone

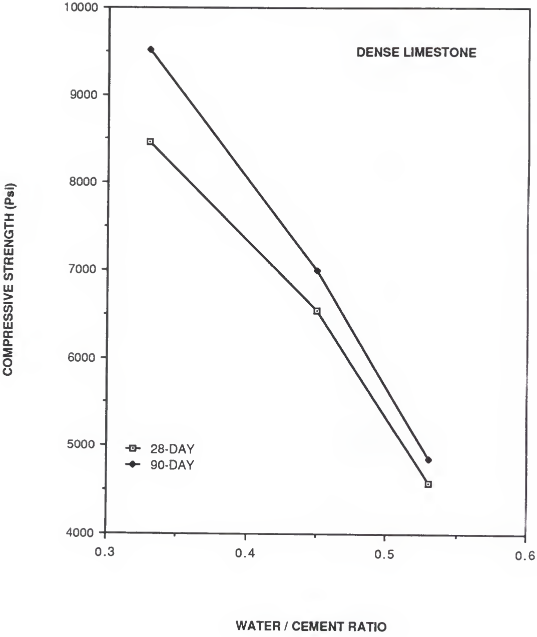

Figure 7.2 Influence of Water/Cement Ratio and Moist Curing Duration on Concrete Strength Using Dense Limestone

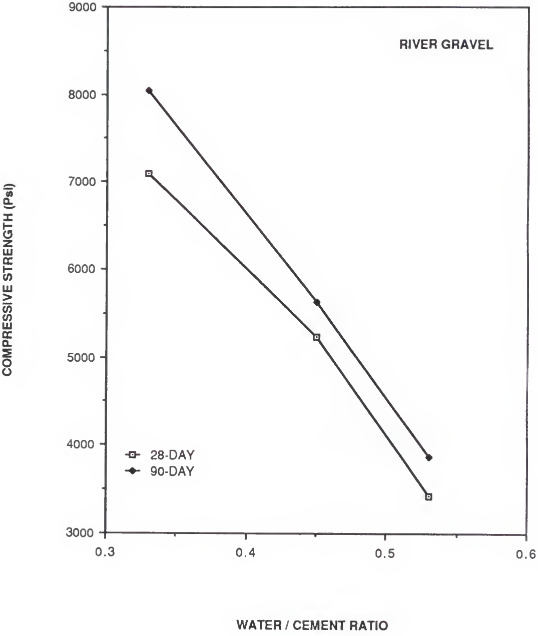

Figure 7.3 Influence of Water/Cement Ratio and Moist Curing Duration on Concrete Strength Using River Gravel

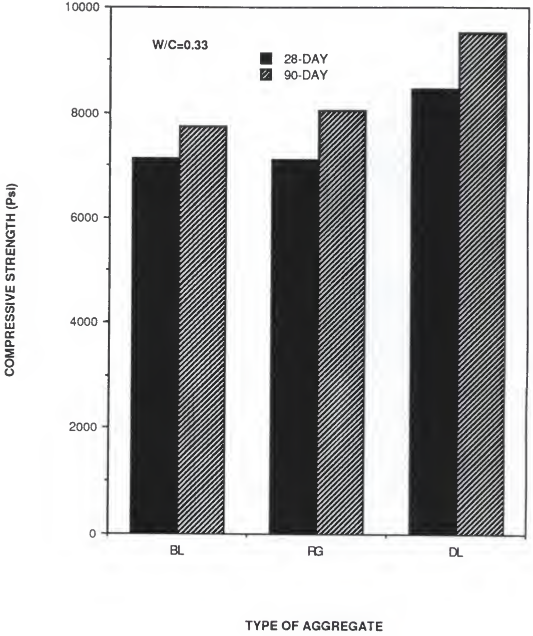

Figure 7.4 Influence of Aggregate Type and Moist Curing Duration on Concrete Strength at W/C = 0.33

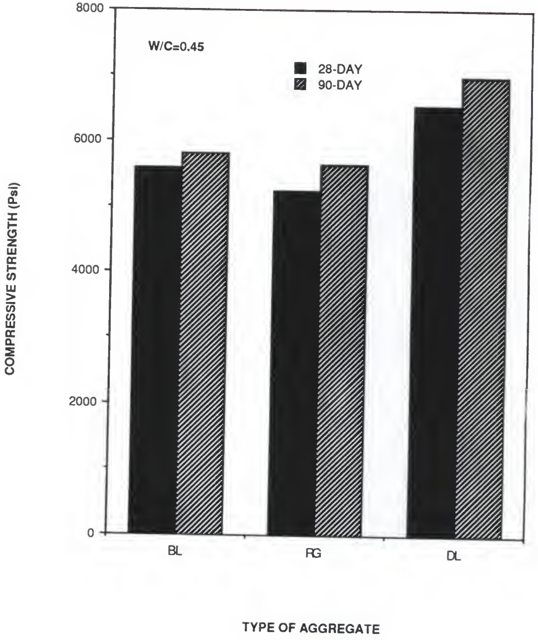

Figure 7.5 Influence of Aggregate Type and Moist Curing Duration on Concrete Strength at W/C = 0.45

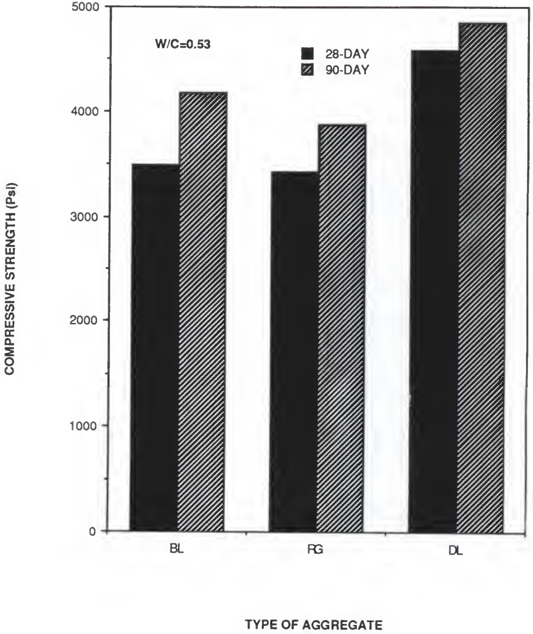

Figure 7.6 Influence of Aggregate Type and Moist Curing Duration on Concrete Strength at W/C = 0.53

ville limestone and river gravel are not significantly different from each other, but both produce strengths which are significantly lower than those by the dense limestone. At a W/C of 0.53, the three aggregates are not significantly different from one another.

2. The compressive strength of hardened concrete increases with a decrease in the water-cement ratio.
3. The compressive strength increases with the age of concrete. For a 28-day moist-cured concrete, the compressive strength varies from about 84% to 96% of that of 90-day moist-cured concrete.

CHAPTER 8
SPLITTING TENSILE STRENGTH OF LABORATORY CONCRETE SPECIMENS

8.1 Introduction

The knowledge of tensile strength of concrete is very important in concrete pavement design because failure of concrete pavements is caused primarily by flexural stresses. Factors affecting the flexural strength of concrete are mortar strength and the bond between the coarse aggregate and the mortar.

Three methods used to determine the tensile strength of concrete are direct tension, flexural strength, and splitting tension tests. At present, there is no standard test using the direct tension method.

Although the splitting tension test is not a true tension test, it is, however, simple to perform and yields a fairly reliable measure of tensile strength [4, 9, 37]. The tensile strength of concrete obtained from the splitting tension test is about 10 to 15 percent higher than the result obtained from direct tension test [9, 36].

The results of the splitting tensile strength and the statistical analyses performed are presented in this chapter.

8.2 Analysis of Results

The results of the splitting tensile strength test on hardened laboratory concrete for the seven experimental designs are presented in

Table 8.1. The same ANOVA models that were used for the analysis of the compressive strength results and which are presented in Chapter 7 were used for the analyses of the splitting tensile strength test results.

8.2.1 Results of Experimental Design No. 1

The objective of this experimental design was to study the effects of aggregate type, water-cement ratio, and curing duration on the splitting tensile strength. Analysis of variance (ANOVA) was performed on the splitting tensile strength test data from Design No. 1 using the ANOVA model as presented in Equation 7.1. The ANOVA results are summarized in Table 8.2.

The aggregate type and water-cement ratio main effects are significant at 5% probability of error. No interaction effect is significant.

A comparison of means for aggregate type and water-cement ratio main effects was performed using the Duncan's test at 5% level of significance. The results are summarized in Tables 8.3 and 8.4.

Brooksville limestone and river gravel are not significantly different. However, the dense limestone produced significantly higher splitting tensile strength than the other two aggregates.

The three levels of water-cement ratio produced significantly dif ferent strength, the lower water-cement ratio producing higher splitting tensile strengths.

8.2.2 Results of Experimental Design No. 2

The results of ANOVA on the splitting tensile strength of the concrete in Design No. 2, which studied the effects of aggregate type and curing duration at a fixed W/C ratio of 0.53, are presented in Table 8.5. At the W/C ratio of 0.53, the effects of aggregate type, curing condition and their interactions are all not significant.

Table 8.1 Results of Splitting Tensile Strength Test on Hardened Concrete

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Splitting Tensile Strength (psi)							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
2 (1a)	0.53	508	BL	1	231	299	324	285	334	346	348	343
				2	361	387	389	379	336	374	383	364
			RG	1	337	339	353	343	326	330	340	332
				2	326	330	379	345	334	356	359	350
			DL	1	316	328	346	330	342	343	359	348
				2	377	473	494	448	418	428	486	444
3 (1b)	0.45	564	BL	1	309	383	477	390	409	430	507	449
				2	392	410	475	426	375	402	487	421
			RG	1	329	342	360	344	364	417	428	403
				2	392	416	422	410	365	384	459	403
			DL	1	483	502	533	506	378	438	489	435
				2	403	442	455	433	446	507	512	488
4 (1c)	0.33	752	BL	1	364	531	544	480	396	446	474	439
				2	382	473	525	460	453	516	540	503
			RG	1	507	531	539	526	496	498	534	509
				2	383	461	551	465	445	454	465	455
			DL	1	458	560	582	533	517	573	699	596
				2	623	629	633	6[illegible]	711	742	803	752

Table 8.1 continued

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Splitting Tensile Strength (psi)							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
5	0.53	508	BL	1	231	299	324	285	334	346	348	343
				2	361	387	389	379	336	374	383	364
		564		1	233	251	297	260	338	342	388	356
				2	323	341	437	367	351	368	404	374
6	0.45	564	BL	1	309	383	477	390	409	430	507	449
				2	392	410	475	426	375	402	487	421
		658		1	440	501	563	501	337	542	559	479
				2	338	437	439	407	366	406	458	410
7	0.45	658	BL	1	(SAME AS IN DESIGN NO. 6)							
				2								
	0.38			1	391	462	503	452	412	417	500	443
				2	412	439	492	448	404	409	427	413

* Design No. 1 data are the same as those for Designs 2-4 combined.

** BL = Brooksville Limestone; RG = River Gravel; DL = Dense Limestone.

Table 8.2 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 1

Source of Variation	df	SS	MS	F	P
A	2	177921	88961	7.49	0.0122*
E	2	526120	263060	22.14	0.0003**
AE	4	54128	13532	1.14	0.3978
B(A*E)	9	106931	11881	-	-
D	1	7684	7684	2.24	0.1685
AD	2	3431	1716	0.50	0.6220
ED	2	1582	791	0.23	0.7984
AED	4	20019	5005	1.46	0.2917
BD(A*E)	9	30835	3426	1.60	0.1315
ε	72	154163	2141	-	-

R-Square = 0.857627

* Significant at $\alpha = 0.05$ level.

** Significant at $\alpha = 0.01$ level.

Table 8.3 Grouping of Aggregate Type by Means of Splitting Tensile Strength of Concrete from Duncan's Test [Design No. 1]

Alpha = 0.05 DF = 9 MSE = 11881

Aggregate Type	Mean	Grouping*
Dense Limestone	495.22	A
Brooksville Limestone	411.44	B
River Gravel	406.97	B

* Note: Means with the same letter are not significantly different.

Table 8.4 Grouping of Water-Cement Ratio by Means of Splitting Tensile Strength of Concrete from Duncan's Test [Design No. 1]

Alpha - 0.05 DF = 9 MSE = 11881

W/C	Mean	Grouping*
0.33	528.83	A
0.45	425.61	B
0.53	359.19	C

* Note: Means with the same letter are not significantly different.

Table 8.5 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 2

Source of Variation	df	SS	MS	F	P
A	2	19967	9984	0.67	0.5749
B(A)	3	44729	14910	-	-
D	1	650	650	0.43	0.5576
AD	2	935	468	0.31	0.7537
BD(A)	3	4507	1502	1.81	0.1730
ε	24	19967	832	-	-

R-Square = 0.779995

8.2.3 Results of Experimental Design No. 3

In Design No. 3, the effects of aggregate type and curing duration at a fixed W/C ratio of 0.45 were studied. ANOVA was performed on the splitting tensile strength of the concrete using the ANOVA model as presented in Equation 7.2. The results are presented in Table 8.6.

At the W/C of 0.45, the effects of aggregate types on the splitting tensile strength are shown to be significant.

A Duncan's test was performed at 5% level of significance with the objective of comparing the means of the effects of the aggregate type. Table 8.7 shows the results of the test.

Brooksville limestone and river gravel are not significantly different. Also, Brooksville limestone and dense limestone are not significantly different. But dense limestone produces significantly higher strength than the river gravel.

8.2.4 Results of Experimental Design No. 4

The results of ANOVA performed on Design No. 4, which studied the effects of aggregate type and curing duration at a fixed W/C ratio of 0.33 and cement content of 752 lb/cy, are summarized in Table 8.8. The main effects (aggregate type and curing duration) and interaction effects in this design are not significant.

8.2.5 Results of Experimental Design No. 5

The effects of the cement content and curing duration given W/C ratio of 0.53 and Brooksville limestone on the splitting tensile strength was studied in this experimental design. ANOVA was performed on the test results using the ANOVA model as presented in Equation 7.3. The results are summarized in Table 8.9. The effects of cement content are seen to be insignificant.

Table 8.6 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 3

Source of Variation	df	SS	MS	F	P
A	2	34834	17417	14.50	0.0287*
B(A)	3	3604	1201	-	-
D	1	2055	2055	0.34	0.6019
AD	2	2406	1203	0.20	0.8304
BD(A)	3	18249	6083	2.92	0.0548
ε	24	50033	2085	-	-

R-Square = 0.549981

* Significant at $\alpha = 0.05$ level.

Table 8.7 Grouping of Aggregate Type by Means of Splitting Tensile Strength of Concrete from Duncan's Test [Design No. 3]

Alpha = 0.05 DF = 3 MSE = 1201

Aggregate Type	Mean	Grouping*
Dense Limestone	465.67	A
Brooksville Limestone	421.33	AB
River Gravel	389.83	B

* Note: Means with the same letter are not significantly different.

Table 8.8 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 4

Source of Variation	df	SS	MS	F	P
A	2	177249	88625	4.54	0.1238
B(A)	3	58598	19533	-	-
D	1	6561	6561	2.44	0.2165
AD	2	20109	10055	3.73	0.1535
BD(A)	3	8079	2693	0.77	0.5232
ε	24	84163	3507	-	-

R-Square = 0.762759

Table 8.9 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	63	63	0.01	0.9462
B(C)	2	21811	10906	-	-
D	1	8030	8030	1.64	0.3291
CD	1	1335	1335	0.27	0.6539
BD(C)	2	9812	4906	4.09	0.0367*
ε	16	19179	1199	-	-

R-Square = 0.681570

* Significant at $\alpha = 0.05$ level.

8.2.6 Results of Experimental Design No. 6

ANOVA was performed on the test results from Design No. 6, which studied the effects of cement content and curing duration given a W/C ratio of 0.45 and Brooksville limestone on the splitting tensile strength, using the ANOVA model as presented in Equation 7.3. The results of the ANOVA are summarized in Table 8.10. Similar to the results of Design No. 6, the effects of cement content, curing duration and their interactions are found to be insignificant.

8.2.7 Results of Experimental Design No. 7

The results of analysis of variance performed on the test results from Design No. 7, which studied the effects of the water-cement ratio and curing duration on splitting tensile strength of concrete batched with Brooksville limestone and a fixed cement content of 658 lb/cy, are summarized in Table 8.11. Neither the main effects nor the interactions were significant. This experimental design covered only two water-cement ratios, namely, 0.38 and 0.45. Due to the variation of the splitting tensile strength results, the difference between the effects of these two W/C ratio was not significant.

8.2.8 Graphical Presentation of Means

The relationships between the water-cement ratio and the splitting tensile strength of concrete for both 28-day and 90-day curing are depicted in Figures 8.1 through 8.3, for the Brooksville limestone, dense limestone and river gravel, respectively.

The comparison of the effects of aggregate type on the splitting tensile strength for water-cement ratios of 0.33, 0.45, and 0.53 are presented in Figures 8.4 through 8.6, respectively.

Table 8.10 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	4538	4538	0.44	0.5762
B(C)	2	20723	10362	-	-
D	1	542	542	0.30	0.6370
CD	1	1908	1908	1.07	0.4097
BD(C)	2	3569	1785	0.36	0.7028
ε	16	79171	4948	-	-

R-Square = 0.283198

Table 8.11 Results of ANOVA on Data from Splitting Tensile Strength Test in Design No. 7

Source of Variation	df	SS	MS	F	P
E	1	580	580	0.05	0.8380
B(E)	2	21534	10767	-	-
D	1	1350	1350	2.59	0.2487
ED	1	267	267	0.51	0.5485
BD(E)	2	1042	521	0.13	0.8787
ε	16	63935	3996	-	-

R-Square = 0.279259

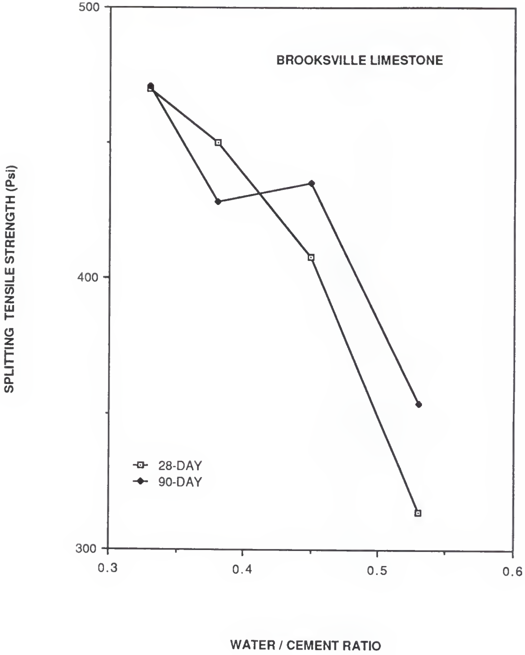

Figure 8.1 Influence of Water/Cement Ratio and Moist Curing Duration on Splitting Tensile Strength of Concrete Using Brooksville Limestone

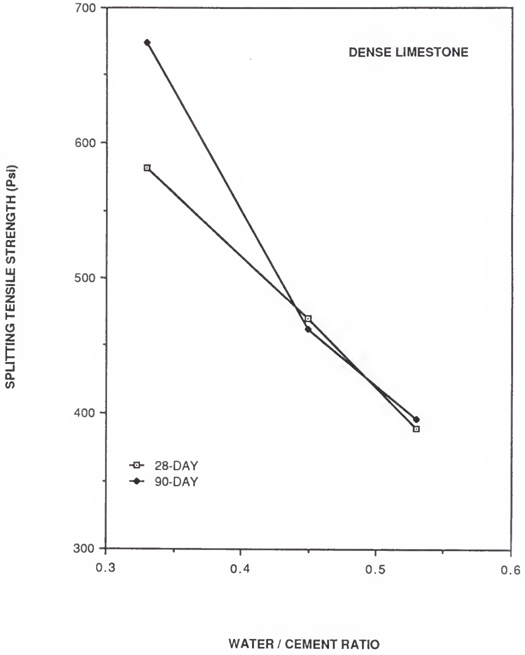

Figure 8.2 Influence of Water/Cement Ratio and Moist Curing Duration on Splitting Tensile Strength of Concrete Using Dense Limestone

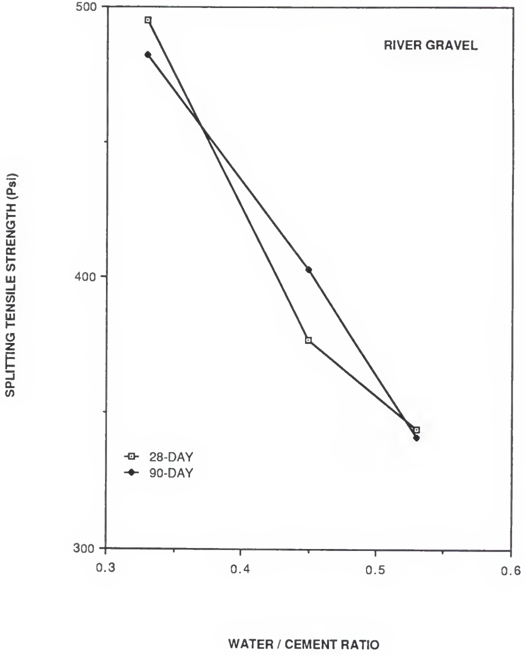

Figure 8.3 Influence of Water/Cement Ratio and Moist Curing Duration on Splitting Tensile Strength of Concrete Using River Gravel

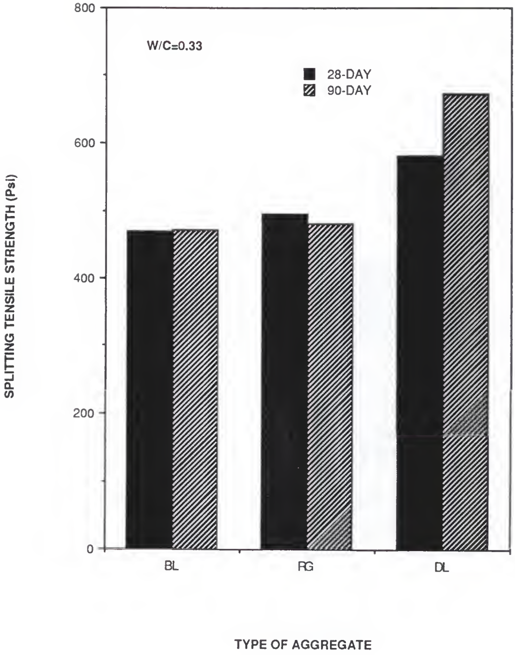

Figure 8.4 Influence of Aggregate Type and Moist Curing Duration on Splitting Tensile Strength of Concrete at W/C = 0.33

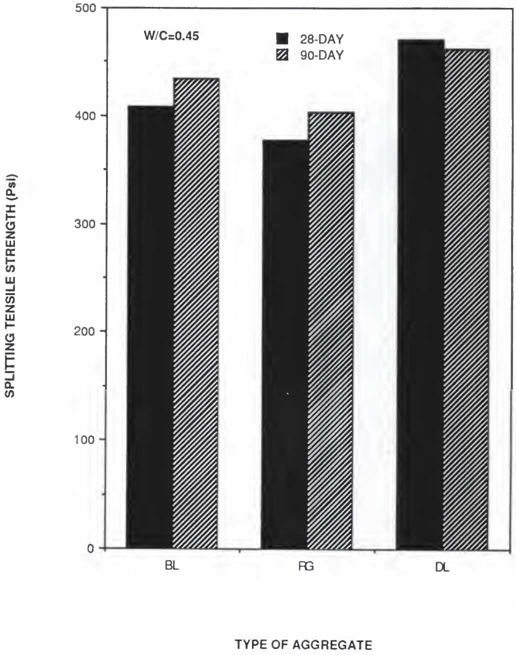

Figure 8.5 Influence of Aggregate Type and Moist Curing Duration on Splitting Tensile Strength of Concrete at W/C = 0.45

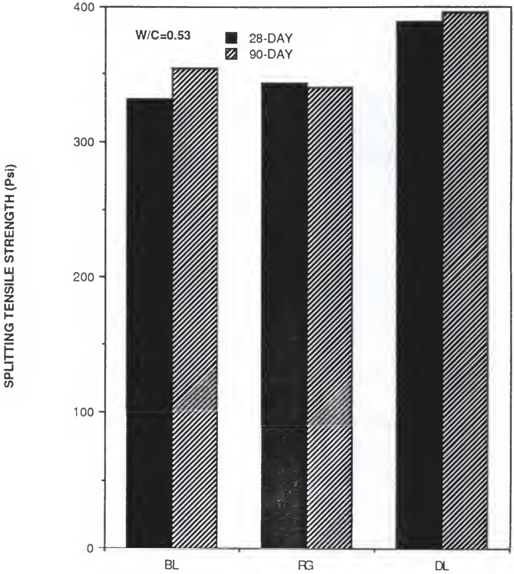

Figure 8.6 Influence of Aggregate Type and Moist Curing Duration on Splitting Tensile Strength of Concrete at W/C = 0.53

8.3 Summary of Findings

The following are the findings from the results of the splitting tensile strength test:

1. Aggregate type has some effect on the splitting tensile strength of concrete. Generally, the Brooksville limestone produces approximately the same splitting tensile strength as the river gravel while the dense limestone produces higher strengths than both these two aggregates.
2. The splitting tensile strength of concrete increases as the water-cement ratio decreases.
3. For a fixed water-cement ratio, changes in cement content do not have any significant effect on the splitting tensile strength.

CHAPTER 9

MODULUS OF RUPTURE OF LABORATORY CONCRETE SPECIMENS

9.1 Introduction

The modulus of rupture of a concrete test beam is the maximum theoretical tensile stress at the bottom fibre of the test beam at rupture and is computed based on the assumption that the concrete behaves linearly elastically until fracture. It is an indication of the flexural or tensile strength of a given concrete.

This chapter presents the results of the modulus of rupture test and the statistical analyses performed.

9.2 Analysis of Results

Table 9.1 displays the results of the modulus of rupture tests on hardened laboratory concrete for the seven experimental designs. The same ANOVA models that were used for the analysis of the compressive strength and splitting tensile strength results and which are presen in Chapter 7 were used for the analysis of the modulus of rupture test results.

9.2.1 Results of Experimental Design No.1

Experimental Design No. 1 investigated the effects of aggregate type, water-cement ratio, and curing duration on the modulus of rupture of hardened laboratory concrete.

Table 9.1 Results of Moduli of Rupture Test on Hardened Concrete

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Moduli of Rupture (psi)							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
2 (1a)	0.53	508	BL	1	609	618	624	617	561	567	597	575
				2	652	696	721	690	565	589	598	584
			RG	1	580	602	609	597	607	630	642	626
				2	549	624	661	611	572	583	613	589
			DL	1	537	559	565	554	569	602	627	599
				2	512	592	626	577	717	726	734	726
3 (1b)	0.45	564	BL	1	591	608	611	603	683	701	722	702
				2	709	749	780	746	674	804	811	763
			RG	1	619	693	699	670	722	758	778	753
				2	580	626	642	616	693	746	749	729
			DL	1	634	677	681	664	820	881	881	861
				2	716	725	731	724	838	886	888	871
4 (1c)	0.33	752	BL	1	778	806	831	805	893	910	939	914
				2	788	816	851	818	800	849	920	856
			RG	1	894	923	923	913	863	986	995	948
				2	800	904	951	885	893	951	982	942
			DL	1	825	846	862	844	1079	1148	1276	1168
				2	878	973	10	977	1216	1234	1366	1272

Table 9.1 continued

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Moduli of Rupture (psi)							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
5	0.53	508	BL	1	609	618	624	617	561	567	597	575
				2	652	696	721	690	565	589	598	584
		564		1	551	590	608	583	542	551	563	552
				2	640	655	676	657	672	673	707	684
6	0.45	564	BL	1	591	608	611	603	683	701	722	702
				2	709	749	780	746	674	804	811	763
		658		1	726	772	775	758	616	741	802	720
				2	628	637	678	648	793	823	845	820
7	0.45	658	BL	1	(SAME AS IN DESIGN NO. 6)							
				2								
	0.38			1	713	715	790	739	775	792	863	810
				2	710	750	799	753	749	808	813	790

* Design No. 1 data is the same as that for Designs 2-4 combined.

** BL = Brooksville Limestone; RG = River Gravel; DL = Dense Limestone.

ANOVA was performed on the test data using the ANOVA model as presented in Equation 7.1. The results of the ANOVA are summarized in Table 9.2.

All the main effects (aggregate type, W/C ratio and curing duration) are highly significant. The interactions of aggregate type with curing duration and water-cement ratio with curing duration are also highly significant.

A comparison of means for the aggregate type and water-cement ratio main effects was performed at 28- and 90-day moist curing durations using the Duncan's test at 5% probability of error level. The results of the comparison are summarized in Tables 9.3 and 9.4.

At 28-day moist cured age, the effects of the three aggregates are not significantly different. However, at 90-day moist curing, the dense limestone produces significantly higher modulus of rupture than both the river gravel and Brooksville limestone which are not significantly different from one another.

At 28-day moist cured age, the water-cement ratios of 0.45 and 0.53 are not significantly different from each other but give significantly lower modulus of rupture than the W/C of 0.33. At 90-day curing, the effects of all the three water-cement ratios are significantly different from one another, the lower W/C producing significantly higher modulus of rupture.

9.2.2 Results of Experimental Design No. 2

The ANOVA results for Design No. 2, which investigated the effects of aggregate type and curing duration on the modulus of rupture of concrete at W/C of 0.53 and cement content of 508 lb/cy are summarized in

Table 9.2 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 1

Source of Variation	df	SS	MS	F	P
A	2	192211	96106	8.16	0.0095**
E	2	2067063	1033532	87.73	0.0001**
AE	4	155082	38771	3.29	0.0636
B(A*E)	9	106025	11781	-	-
D	1	204276	204276	72.40	0.0001**
AD	2	154821	77411	27.44	0.0001**
ED	2	87079	43540	15.43	0.0012**
AED	4	34748	8687	3.08	0.0743
BD(A*E)	9	25394	2822	1.39	0.2085
ε	72	146081	2029	-	-

R-Square = 0.953958

** Significant at $\alpha = 0.01$ level.

Table 9.3 Grouping of Aggregate Type by Means of Modulus of Rupture of Concrete from Duncan's Test [Design No. 1]

Duration = 28-day: Alpha = 0.05 DF = 9 MSE = 8598

Duration = 90-day: Alpha = 0.05 DF = 9 MSE = 6004

Moist Curing Duration	Aggregate Type	Mean	Grouping*
28 - day	Dense Limestone	723.33	A
	River Gravel	715.50	A
	Brooksville Limestone	713.22	A
90 - day	Dense Limestone	916.00	A
	River Gravel	764.61	B
	Brooksville Limestone	732.39	B

* Note: Means at each moist curing duration with the same letter are not significantly different.

Table 9.4 Grouping of Water-Cement Ratio by Means of Modulus of Rupture of Concrete from Duncan's Test [Design No. 1]

Duration = 28-day: Alpha = 0.05 DF = 9 MSE = 8598

Duration = 90-day: Alpha = 0.05 DF = 9 MSE = 6004

Moist Curing Duration	Water-Cement Ratio	Mean	Grouping*
28 - day	0.33	873.89	A
	0.45	670.61	B
	0.53	607.56	B
90 - day	0.33	1016.67	A
	0.45	779.72	B
	0.53	616.61	C

* Note: Means at each moist curing duration with the same letter are not significantly different.

Table 9.5. At the W/C of 0.53, the effects of aggregate type and curing duration are shown to be insignificant.

9.2.3 Results of Experimental Design No. 3

ANOVA was performed on the test results from Design No. 3, which studied the effects of aggregate type and moist curing duration at a fixed W/C of 0.45 and cement content of 564 lb/cy. The results are presented in Table 9.6. At the W/C of 0.45, the difference between 28-day curing and 90-day curing is significant, while the effect of aggregate type is not significant.

9.2.4 Results of Experimental Design No. 4

Table 9.7 summarizes the results of the analysis of variance using ANOVA performed on the test data from Design No. 4. The effects studied in this experimental design are the same as those of Design 3 except that the water-cement ratio is 0.33 and the cement content is 752 lb/cy.

At the W/C of 0.33, the aggregate type and curing duration main effects are significant at the 5% probability of error level. Also, the interaction of the aggregate type with curing duration is significant.

The means of the aggregate type were compared at 28- and 90-day moist curing durations using the Duncan's multiple comparison range test. The results are displayed in Table 9.8. At 28-day curing, the effects of the three aggregates are not significantly different from one another. At 90-day curing, the dense limestone produces significantly higher modulus of rupture than the other two aggregates.

9.2.5 Results of Experimental Design No. 5

The ANOVA results for Design No. 5, which studied the effects of cement content and moist curing duration on the modulus of rupture of

Table 9.5 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 2

Source of Variation	df	SS	MS	F	P
A	2	706	353	0.05	0.9539
B(A)	3	22113	7371	-	-
D	1	738	738	0.17	0.7078
AD	2	44078	22039	5.08	0.1089
BD(A)	3	13025	4342	4.84	0.0089**
ε	24	21507	896	-	-

R-Square = 0.789488

** Significant at $\alpha = 0.01$ level.

Table 9.6 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 3

Source of Variation	df	SS	MS	F	P
A	2	54586	27293	2.08	0.2709
B(A)	3	39309	13103	-	-
D	1	108147	107147	42.31	0.0074**
AD	2	20009	10005	3.95	0.1444
BD(A)	3	7598	2533	1.98	0.1432
ε	24	30628	1276	-	-

R-Square = 0.881872

** Significant at $\alpha = 0.01$ level.

Table 9.7 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 4

Source of Variation	df	SS	MS	F	P
A	2	292001	146001	9.82	0.0482*
B(A)	3	44604	14868	-	-
D	1	183469	183469	115.36	0.0017**
AD	2	125482	62741	39.45	0.0070**
BD(A)	3	4771	1590	0.41	0.7498
ε	24	93946	3914	-	-

R-Square = 0.873775

* Significant at $\alpha = 0.05$ level.

** Significant at $\alpha = 0.01$ level.

Table 9.8 Grouping of Aggregate Type by Means of Modulus of Rupture of Concrete from Duncan's Test [Design No. 4]

Duration = 28-day: Alpha = 0.05 DF = 3 MSE = 9335

Duration = 90-day: Alpha = 0.05 DF = 3 MSE = 7123

Moist Curing Duration	Aggregate Type	Mean	Grouping*
28 - day	Dense Limestone	910.83	A
	River Gravel	899.17	A
	Brooksville Limestone	811.67	A
90 - day	Dense Limestone	1219.83	A
	River Gravel	945.00	B
	Brooksville Limestone	885.17	B

* Note: Means at each moist curing duration with the same letter are not significantly different.

concrete using a fixed W/C of 0.53 and Brooksville limestone are summarized in Table 9.9. The analysis was performed using the ANOVA model as expressed by Equation 7.3. The effects of cement content and curing duration are shown to be not significant.

9.2.6 Results of Experimental Design No. 6

The results of analysis of variance performed on the data in Design No. 6 which studied the effects of cement content and curing duration given a W/C of 0.45 and Brooksville limestone are summarized in Table 9.10. The effects of cement content and curing duration are shown to be not significant.

9.2.7 Results of Experimental Design No. 7

Analysis of variance was performed on the test results from Design No. 7, which studied the effects of water-cement ratio and curing duration on the modulus of rupture of concrete using Brooksville limestone and a fixed cement content of 658 lb/cy. The results of the ANOVA are summarized in Table 9.11. The effect of W/C is shown to be significant.

9.2.8 Graphical Presentation of Means

Figure 9.1 through 9.3 shows the influence of the water-cement ratio and moist curing duration on the modulus of rupture of concrete for the Brooksville limestone, dense limestone and river gravel, respectively.

The means of the modulus of rupture for each aggregate type at water-cement ratios of 0.33, 0.45, and 0.53 are shown in Figures 9.4 through 9.6, respectively.

Table 9.9 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	40	40	0.00	0.9670
B(C)	2	36829	18415	-	-
D	1	8626	8626	3.10	0.2203
CD	1	7740	7740	2.78	0.2372
BD(C)	2	5563	2782	6.14	0.0105*
ERROR	16	7249	453	-	-

R-Square = 0.890250

* Significant at $\alpha = 0.05$ level.

Table 9.10 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	6435	6435	0.41	0.5864
B(C)	2	31175	15588	-	-
D	1	23500	23500	1.23	0.3833
CD	1	135	135	0.01	0.9406
BD(C)	2	38287	19144	8.12	0.0037**
ε	16	37707	2357	-	-

R-Square = 0.725247

** Significant at $\alpha = 0.01$ level.

Table 9.11 Results of ANOVA on Data from Modulus of Rupture Test in Design No. 7

Source of Variation	df	SS	MS	F	P
E	1	8103	8103	169.85	0.0058**
B(E)	2	95	48	-	-
D	1	22022	22022	1.29	0.3738
ED	1	273	273	0.02	0.9109
BD(E)	2	34135	17068	7.38	0.0054**
ε	16	36991	2312	-	-

R-Square = 0.635987

** Significant at $\alpha = 0.01$ level.

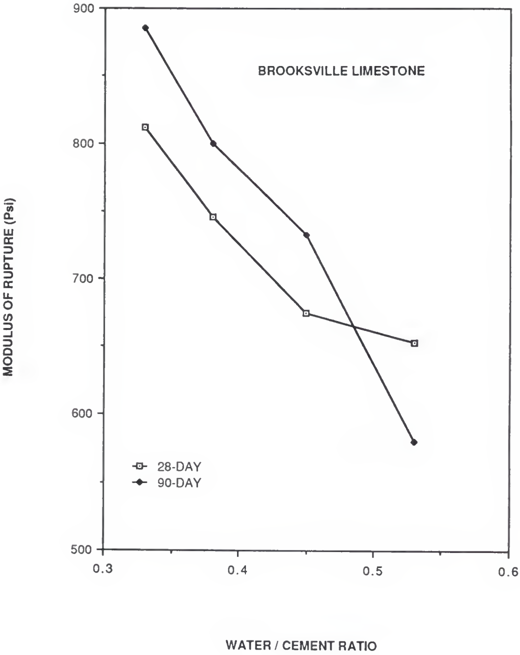

Figure 9.1 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Rupture of Concrete Using Brooksville Limestone

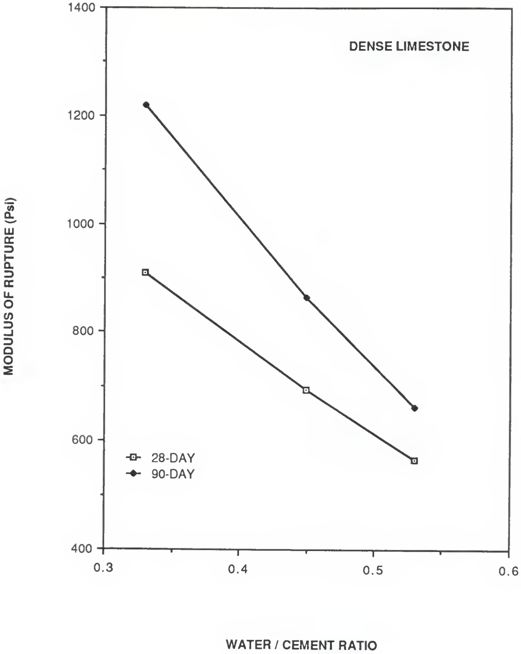

Figure 9.2 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Rupture of Concrete Using Dense Limestone

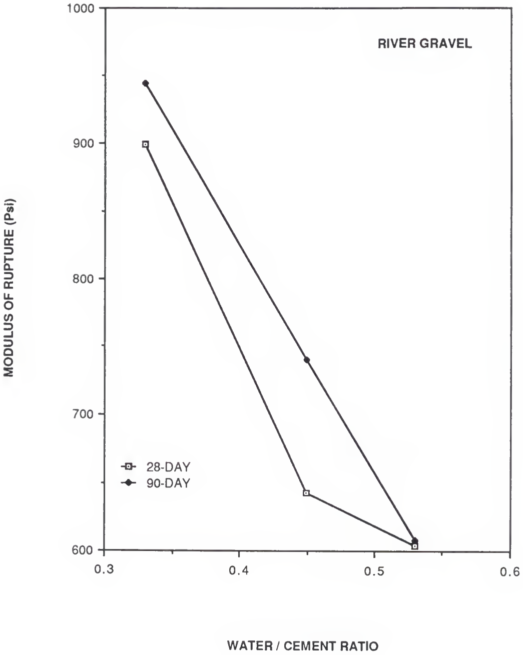

Figure 9.3 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Rupture of Concrete Using River Gravel

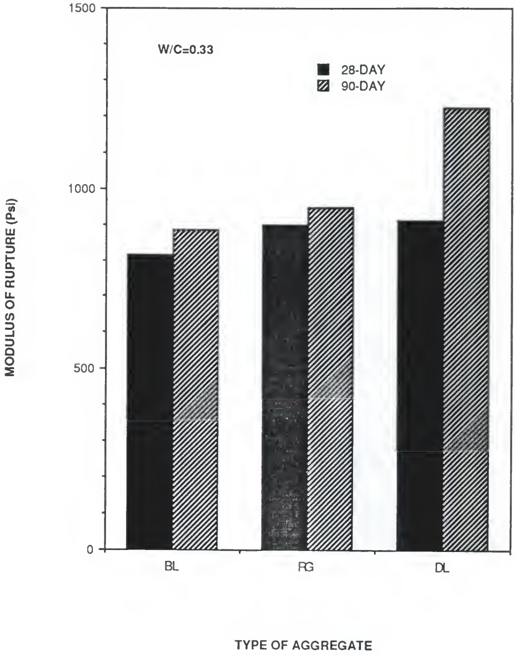

Figure 9.4 Influence of Aggregate Type and Moist Curing Duration on Modulus of Rupture of Concrete at W/C = 0.33

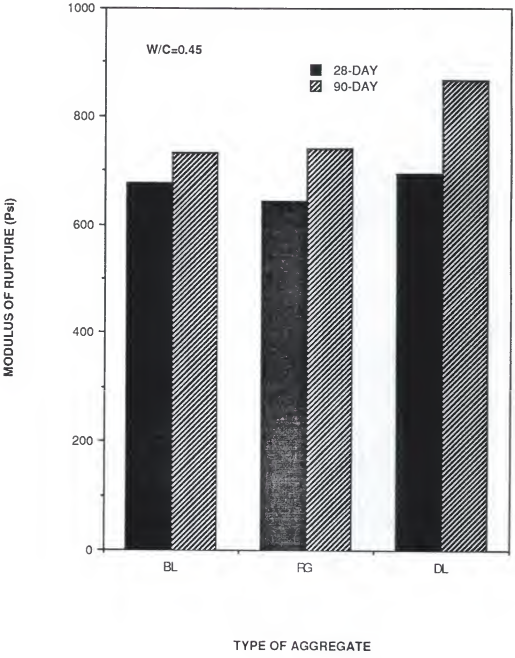

Figure 9.5 Influence of Aggregate Type and Moist Curing Duration on Modulus of Rupture of Concrete at W/C = 0.45

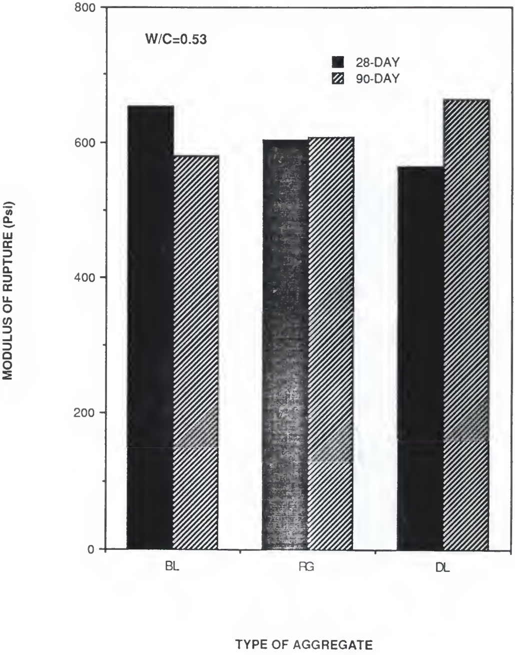

Figure 9.6 Influence of Aggregate Type and Moist Curing Duration on Modulus of Rupture of Concrete at W/C = 0.53

9.3 Summary of Findings

The modulus of rupture test on laboratory concrete specimens yielded the following facts:

1. The aggregate type has some effect on the modulus of rupture of concrete. At 28-day moist-cured age, all the three types of aggregates produce moduli of rupture which are not significantly different from each other. However, at 90-day moist curing, the dense limestone produces significantly higher modulus of rupture than both the river gravel and Brooksville limstone.
2. The water-cement ratio has significant effect on the concrete modulus of rupture. The modulus of rupture generally increases as the water-cement ratio decreases.
3. The modulus of rupture generally increases with the age of moist curing.
4. For a fixed water-cement ratio, changes in cement content do not have any significant effect on the modulus of rupture of concrete.

CHAPTER 10
STATIC MODULUS OF ELASTICITY OF LABORATORY CONCRETE SPECIMENS

10.1 Introduction

The ratio of stress to strain in the elastic range of stress-strain curve is termed static modulus of elasticity or Young's modulus.

This chapter presents the results of the static modulus of elasticity of concrete test and the statistical analyses performed.

10.2 Analysis of Results

Table 10.1 presents the results of the static modulus of elastic test on hardened laboratory concrete for all the seven experimental designs. The same ANOVA models, which are presented in Chapter 7, were used for the analysis of the modulus of elasticity data.

10.2.1 Results of Experimental Design No. 1

Analysis of variance was performed on the test data from Design 1, which studied the effects of aggregate type, water-cement ratio, and curing duration on the modulus of elasticity of the hardened laboratory concrete. The results of the ANOVA are summarized in Table 10.2.

All the main effects (aggregate type, W/C and curing duration) are highly significant with a probability of error level of less than 1%.

A comparison of means for aggregate type and water-cement ratio was performed using the Duncan's test and the results summarized in Tables 10.3 and 10.4, respectively. From Table 10.3, it can be seen that the

Table 10.1 Results of Modulus of Elasticity Test on Hardened Concrete

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Moduli of Elasticity (x 10^6 psi) 28-Day Moist Curing	Moduli of Elasticity (x 10^6 psi) 90-Day Moist Curing
2 (1a)	0.53	508	BL	1	4.12	3.96
				2	4.12	4.22
			RG	1	4.19	4.76
				2	4.46	4.62
			DL	1	5.90	5.75
				2	5.96	6.15
3 (1b)	0.45	564	BL	1	4.60	4.64
				2	4.96	5.41
			RG	1	4.91	5.30
				2	4.94	5.36
			DL	1	6.04	6.66
				2	6.38	6.93
4 (1c)	0.33	752	BL	1	5.10	5.16
				2	4.89	4.82
			RG	1	5.45	5.55
				2	5.40	6.16
			DL	1	6.21	6.98
				2	6.[illegible]	7.08

Table 10.1 continued

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Moduli of Elasticity (x 10^6 psi) 28-Day Moist Curing	90-Day Moist Curing
5	0.53	508	BL	1	4.12	3.96
				2	4.12	4.22
		564		1	3.81	3.75
				2	3.82	4.44
6	0.45	564	BL	1	4.60	4.64
				2	4.96	5.41
		658		1	4.50	4.69
				2	4.15	4.33
7	0.45	658	BL	1	(Same as in Design No. 6)	
				2		
	0.38			1	5.48	5.65
				2	5.21	5.58

* Design No. 1 data is the same as that for Designs 2-4 combined.

** BL = Brooksville Limstone; RG - River Gravel; DL = Dense Limestone

Table 10.2 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 1

Source of Variation	df	SS	MS	F	P
A	2	1979.06E10	989.53E10	113.75	0.0001**
E	2	573.03E10	286.52E10	32.93	0.0001**
AE	4	22.40E10	5.61E10	0.64	0.6443
B(A*E)	9	78.30E10	8.70E10	-	-
D	1	70.00E10	70.00E10	19.68	0.0016**
AD	2	19.80E10	9.90E10	2.78	0.1145
ED	2	13.25E10	6.63E10	1.86	0.2103
AED	4	10.02E10	2.51E10	0.70	0.6086
BD(A*E)	9	32.01E10	3.56E10	-	-
ε	0	0	0	-	-

** Significant at $\alpha = 0.01$ level.

Table 10.3 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete from Duncan's Test [Design No. 1]

Alpha = 0.05 DF = 9 MSE = 8.7E10

Aggregate Type	Mean	Grouping*
Dense Limestone	6410000	A
River Gravel	5090000	B
Brooksville Limestone	4670000	C

* Note: Means with different letters are significantly different.

Table 10.4 Grouping of Water-Cement Ratio by Means of Modulus of Elasticity of Concrete from Duncan's Test [Design No. 1]

Alpha = 0.05 DF = 9 MSE = 8.7E10

W/C	Mean	Grouping*
0.33	5810000	A
0.45	5510000	B
0.53	4850000	C

* Note: Means with different letters are significantly different.

dense limestone produces significantly higher elastic modulus than the river gravel, while the river gravel produces signficantly higher elastic modulus than the Brooksville limestone. From Table 10.4, it is seen that the elastic modulus increases significantly as the W/C decreases.

10.2.2 Results of Experimental Design No. 2

The main objective in Design No. 2 was to study the effects of aggregate type and moist curing duration at a fixed water-cement ratio of 0.53 and cement content of 508 lb/cy on the modulus of elasticity of concrete. ANOVA was performed on the test results using the ANOVA model as presented in Equation 7.2. The analysis results are presented in Table 10.5. The effect of aggregate type is found to be significant.

Table 10.6 summarizes the results of aggregate type means comparison using the Duncan's multiple range test at 5% significance level. The dense limestone produces significantly higher elastic modulus than the river gravel which produces significantly higher elastic modulus than the Brooksville limestone.

10.2.3 Results of Experimental Design No. 3

In Design No. 3, the effects of the aggregate type and moist curing duration at a fixed water-cement ratio of 0.45 and cement content of 564 lb/cy was studied. ANOVA was performed on the test results using the same model as for Design No. 2. The results of the analysis are presented in Table 10.7. All the main effects (aggregate type and curing duration) are significant. A Duncan test was performed to compare the mean effects of aggregate type and the results summarized in Table 10.8. The dense limestone produces significantly higher elastic modulus than the river gravel and the Brooksville limestone, which are not significantly different from one another.

Table 10.5 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 2

Source of Variation	df	SS	MS	F	P
A	2	744.17E10	372.09E10	150.79	0.0010**
B(A)	3	7.40E10	2.47E10	-	-
D	1	4.20E10	4.20E10	1.43	0.3170
AD	2	9.25E10	4.63E10	1.58	0.3398
BD(A)	3	8.78E10	2.93E10	-	-
ε	0	0	0	-	-

** Significant at $\alpha = 0.01$ level.

Table 10.6 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete from Duncan's Test [Design No. 2]

Alpha = 0.05 DF = 3 MSE = 2.5E10

Aggregate Type	Mean	Grouping*
Dense Limestone	5940000	A
River Gravel	4510000	B
Brooksville Limestone	4110000	C

* Note: Means with different letters are significantly different.

Table 10.7 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 3

Source of Variation	df	SS	MS	F	P
A	2	600.17E10	300.08E10	21.73	0.0164*
B(A)	3	41.43E10	13.81E10	-	-
D	1	50.84E10	50.84E10	35.08	0.0096**
AD	2	5.79E10	2.90E10	2.00	0.2810
BD(A)	3	4.35E10	1.45E10	-	-
ε	0	0	0	-	-

* Significant at $\alpha = 0.05$ level.

** Significant at $\alpha = 0.01$ level.

Table 10.8 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete from Duncan's Test [Design No. 3]

Alpha = 0.05 DF = 3 MSE = 1.4E11

Aggregate Type	Mean	Grouping*
Dense Limestone	6500000	A
River Gravel	5130000	B
Brooksville Limestone	4900000	B

* Note: Means with the same letter are not significantly different.

10.2.4 Results of Experimental Design No. 4

Design No. 4 studied the effects of aggregate type and moist curing duration at a fixed water-cement ratio of 0.33 and cement content of 752 lb/cy. ANOVA was performed on the test results using the same ANOVA model as that used for Designs 2 and 3. The analysis results are summarized in Table 10.9. Aggregate type effect is found to be significant at 1% level.

Duncan's multiple range test was used to compare the aggregate type means at 5% level of significance and the results presented in Table 10.10. Dense limestone produces significantly higher elastic modulus than both the river gravel and Brooksville limestone. The effects of river gravel and Brooksville limestone are not significantly different from one another.

10.2.5 Results of Experimental Design No. 5

ANOVA was performed on the test restults from Design No. 5, which studied the effects of cement content and curing duration on the elastic modulus of concrete using a fixed water-cement ratio of 0.53 and Brooksville limestone. The ANOVA results are summarized in Table 10.11. None of the sources of variation (cement content and curing duration) is significant.

10.2.6 Results of Experimental Design No. 6

The objective of this design and Design No. 5 are the same except that the water-cement ratio is 0.45. ANOVA was performed on the test results. The ANOVA results are summarized in Table 10.12. Similar to the results of Design No. 5, all the main effects and interactions are not significant.

Table 10.9 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 4

Source of Variation	df	SS	MS	F	P
A	2	657.16E10	328.58E10	33.45	0.0089**
B(A)	3	29.47E10	9.82E10	-	-
D	1	28.21E10	28.21E10	4.48	0.1245
AD	2	14.78E10	7.39E10	1.17	0.4200
BD(A)	3	18.88E10	6.29E10	-	-
ε	0	0	0	-	-

** Significant at $\alpha = 0.01$ level.

Table 10.10 Grouping of Aggregate Type by Means of Modulus of Elasticity of Concrete from Duncan's Test [Design No. 4]

Alpha = 0.05 DF = 3 MSE = 9.8E10

Aggregate Type	Mean	Grouping*
Dense Limestone	6780000	A
River Gravel	5640000	B
Brooksville Limestone	4990000	B

* Note: Means with the same letter are not significantly different.

Table 10.11 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	4.50E10	4.50E10	0.65	0.5060
B(C)	2	13.94E10	6.97E10	-	-
D	1	3.13E10	3.13E10	0.47	0.5631
CD	1	4.81E10	4.81E10	0.73	0.4841
BD(C)	2	13.25E10	6.63E10	-	-
ε	0	0	0	-	-

Table 10.12 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	47.05E10	47.05E10	2.11	0.2832
B(C)	2	44.53E10	6.97E10	-	-
D	1	9.25E10	9.25E10	4.40	0.1709
CD	1	0.18E10	0.18E10	0.09	0.7974
BD(C)	2	4.21E10	2.10E10	-	-
ε	0	0	0	-	-

10.2.7 Results of Experimental Design No. 7

Design No. 7 evaluated the effects of water-cement ratio and curing duration given Brooksville limestone and a fixed cement content of 658 lb/cy on the modulus of elasticity of concrete. The test results were analyzed and the outcome summarized in Table 10.13. All the main effects (W/C and curing duration) are significant.

10.2.8 Graphical Presentation of Means

Figures 10.1 through 10.3 show the influence of the water-cement ratio and moist curing duration on the modulus of elasticity of concret for Brooksville limestone, dense limestone, and river gravel, respectively.

The means of the modulus of elasticity for each aggregate type at water-cement ratios of 0.33, 0.45, and 0.53 are plotted in Figures 10.4 through 10.6 for water-cement ratios of 0.33, 0.45 and 0.53, respectively.

10.3 Summary of Findings

The findings of the modulus of elasticity test are summarized as follows:

1. The effect of aggregate type is highly significant. All the three aggregate types are significantly different from each other. Dense limestone yielded the highest modulus of elasticity followed by river gravel and lastly Brooksville limestone.

Table 10.13 Results of ANOVA on Data from Modulus of Elasticity Test in Design No. 7

Source of Variation	df	SS	MS	F	P
E	1	225.78E10	225.78E10	29.15	0.0326*
B(E)	2	15.49E10	7.75E10	-	-
D	1	10.35E10	10.35E10	20.65	0.0452*
ED	1	0.36E10	0.36E10	0.72	0.4853
BD(E)	2	1.00E10	0.50E10	-	-
ε	0	0	0	-	-

* Significant at $\alpha = 0.05$ level.

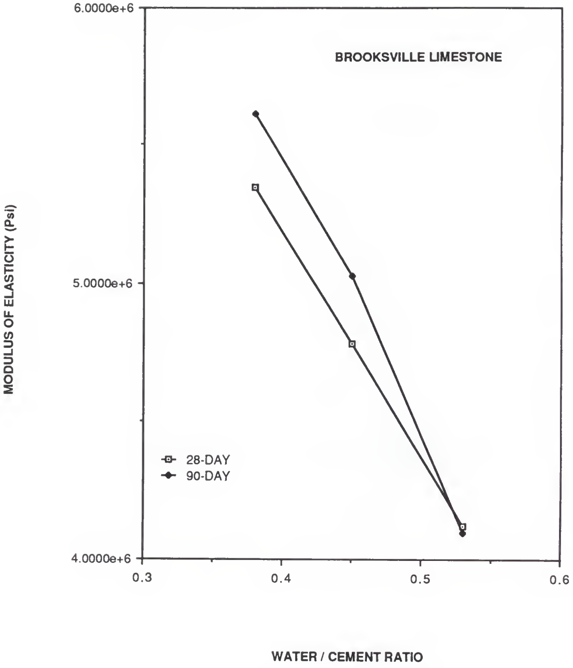

Figure 10.1 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Elasticity of Concrete Using Brooksville Limestone

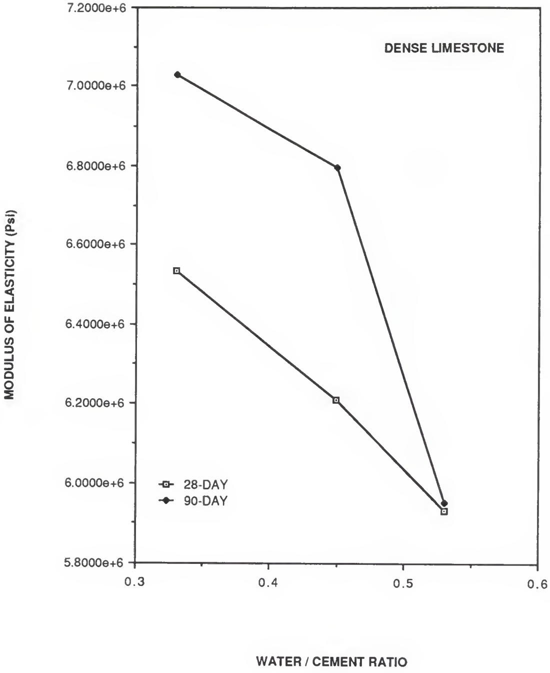

Figure 10.2 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Elasticity of Concrete Using Dense Limestone

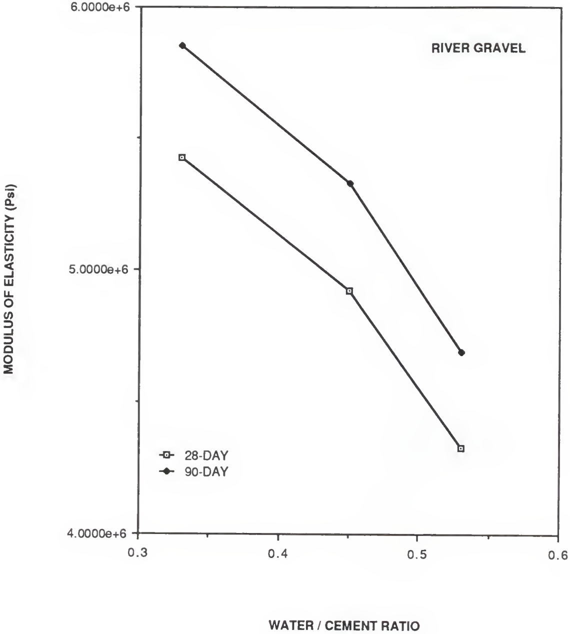

Figure 10.3 Influence of Water/Cement Ratio and Moist Curing Duration on Modulus of Elasticity of Concrete Using River Gravel

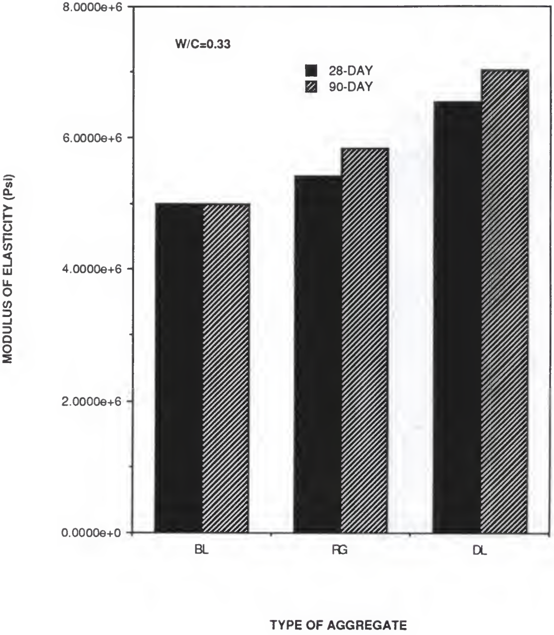

Figure 10.4 Influence of Aggregate Type and Moist Curing Duration on Modulus of Elasticity of Concrete at W/C = 0.33

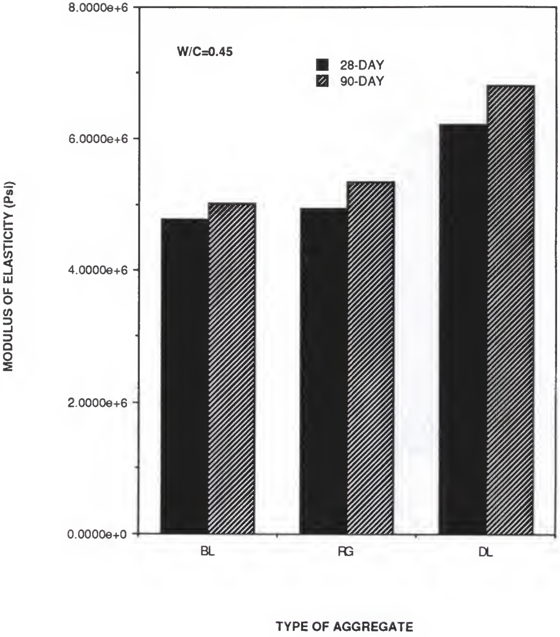

Figure 10.5 Influence of Aggregate Type and Moist Curing Duration on Modulus of Elasticity of Concrete at W/C = 0.45

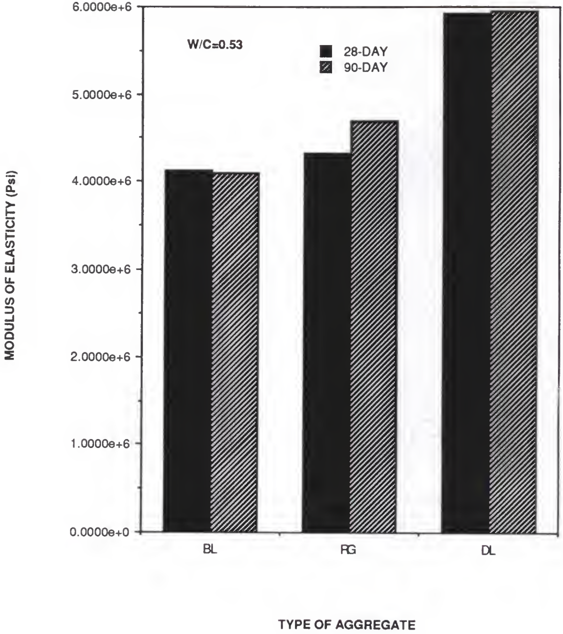

Figure 10.6 Influence of Aggregate Type and Moist Curing Duration on Modulus of Elasticity of Concrete at W/C = 0.53

2. The effects of the three water-cement ratios are significantly different from each other. The modulus of elasticity increases as the water-cement ratio decreases.
3. The age of moist-cured concrete does affect the modulus of elasticity. The elastic modulus increases with moist curing duration.
4. For a fixed water-cement ratio, changes in cement content do not affect the modulus of elasticity of concrete significantly.

CHAPTER 11
COEFFICIENT OF LINEAR THERMAL EXPANSION OF LABORATORY CONCRETE SPECIMENS

11.1 Introduction

The factors affecting the coefficient of linear thermal expansion of concrete have previously been discussed in Chapter 4. Earlier in Chapter 2, the components of thermal expansion were presented and elucidated.

The results of the coefficient of linear thermal expansion of water-saturated and over-dried laboratory concrete specimens and statistical analyses performed are presented in this chapter.

11.2 Experimental Results

Tables 11.1 and 11.2 displays the results of the coefficient of linear thermal expansion test on water-saturated and oven-dried laboratory concrete specimens, respectively.

11.3 Analysis of Results

11.3.1 Analysis of Means

Initially, both the means of the water-saturated and oven-dried test results were analyzed using the Student's T test to determine whether or not there is difference between the two measurements. A single-sample analysis was applied to the difference between the water-saturated and oven-dried measurements. The same experimental unit

Table 11.1 Results of Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimens

Design No.	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Coefficient of Linear Thermal Expansion (Water-Saturated) x 10^{-6}/°F							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
2	0.53	508	BL	1	5.47	5.74	-	5.61	5.50	6.15	6.51	6.05
(1a)				2	5.02	5.14	-	5.08	5.04	5.36	5.37	5.26
			RG	1	6.83	6.47	6.42	6.57	6.78	6.89	6.96	6.88
				2	7.25	7.19	7.04	7.16	6.04	6.41	6.70	6.38
			DL	1	6.12	6.21	-	6.17	5.00	5.20	5.74	5.31
				2	5.87	5.61	6.80	6.09	5.79	5.84	6.10	5.91
3	0.45	564	BL	1	5.55	5.34	5.59	5.49	5.20	5.26	5.42	5.29
(1b)				2	5.33	5.25	-	5.29	4.65	4.89	5.44	4.99
			RG	1	6.12	6.05	6.28	6.15	6.51	6.62	6.95	6.69
				2	6.61	6.51	6.71	6.61	6.08	6.30	6.39	6.26
			DL	1	5.91	5.69	5.50	5.70	5.17	5.75	6.12	5.68
				2	5.98	5.99	6.13	6.03	6.32	6.33	6.37	6.34
4	0.33	752	BL	1	5.58	5.13	5.88	5.53	5.10	5.61	5.75	5.49
(1c)				2	5.74	5.74	5.81	5.76	4.99	5.38	5.55	5.31
			RG	1	6.68	6.80	7.11	6.86	5.85	5.89	5.94	5.89
				2	6.07	5.71	-	5.89	6.05	6.37	6.46	6.29
			DL	1	[illegible]	5.39	6.06	5.78	5.27	5.57	5.63	5.49
				2	[illegible]	5.68	5.11	5.43	5.74	6.22	6.25	6.07

Table 11.1 continued

Design No.	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Coefficient of Linear Thermal Expansion (Water-Saturated) x 10^{-6}/°F							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
5	0.53	508	BL	1	5.47	5.74	-	5.61	5.50	6.15	6.51	6.05
				2	5.02	5.14	-	5.08	5.04	5.36	5.37	5.26
		564		1	4.81	5.40	-	5.11	5.02	5.50	-	5.26
				2	5.64	6.19	6.32	6.05	5.26	5.40	5.53	5.40
6	0.45	564	BL	1	5.55	5.34	5.59	5.49	5.20	5.26	5.42	5.29
				2	5.33	5.25	-	5.29	4.65	4.89	5.44	4.99
		658		1	4.92	4.91	-	4.92	4.94	5.43	5.50	5.29
				2	5.59	5.62	5.68	5.63	5.54	5.55	5.59	5.56

** BL = Brooksville Limestone; RG = River Gravel; DL = Dense Limestone.

Table 11.2 Results of Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens

Design No.	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Coefficient of Linear Thermal Expansion (Oven-Dried) x 10^{-6}/°F							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
2	0.53	508	BL	1	5.03	5.13	5.64	5.27	5.17	5.52	5.53	5.41
(1a)				2	4.99	5.39	5.51	5.30	5.89	5.99	6.01	5.96
			RG	1	7.59	7.60	8.52	7.90	6.88	7.00	7.77	7.22
				2	7.35	7.64	7.72	7.57	6.62	6.66	6.82	6.70
			DL	1	6.30	6.32	6.44	6.35	5.45	6.23	6.66	6.11
				2	6.04	6.47	6.67	6.39	5.39	5.72	6.08	5.73
3	0.45	564	BL	1	6.00	6.00	6.57	6.19	5.94	6.11	6.37	6.14
(1b)				2	4.83	4.83	5.41	5.02	5.38	5.54	6.11	5.68
			RG	1	7.37	7.72	7.73	7.61	6.97	7.23	7.27	7.16
				2	7.44	7.86	7.95	7.75	7.00	7.16	7.26	7.14
			DL	1	6.17	6.26	6.41	6.28	4.97	5.49	5.84	5.43
				2	5.91	6.00	6.02	5.98	5.20	5.83	6.02	5.68
4	0.33	752	BL	1	5.71	5.83	6.48	6.01	6.03	6.48	6.49	6.33
(1c)				2	5.93	6.06	6.17	6.05	5.17	5.77	5.78	5.57
			RG	1	7.06	7.68	7.73	7.49	5.65	5.71	6.00	5.79
				2	7.19	7.41	7.81	7.47	6.44	6.68	6.73	6.62
			DL	1	[illegible]	5.93	5.96	[illegible]	5.63	6.36	6.40	6.13
				2	[illegible]	6.14	6.41	[illegible]	5.68	6.00	6.06	5.91

Table 11.2 continued

Design No.	W/C	Cement Content (lb/cy)	Aggregate Type ** (Max. Size=3/8")	Replicate	Coefficient of Linear Thermal Expansion (Oven-Dried) x 10^{-6}/°F							
					28-Day Moist Curing				90-Day Moist Curing			
					Specimens			Average	Specimens			Average
					1	2	3		1	2	3	
5	0.53	508	BL	1	5.03	5.13	5.64	5.27	5.17	5.52	5.53	5.41
				2	4.99	5.39	5.51	5.30	5.89	5.99	6.01	5.96
		564		1	4.47	4.87	-	4.67	5.59	6.32	-	5.96
				2	5.56	5.96	6.72	6.08	6.06	6.11	6.14	6.10
6	0.45	564	BL	1	6.00	6.00	6.57	6.19	5.94	6.11	6.37	6.14
				2	4.83	4.83	5.41	5.02	5.38	5.54	6.11	5.68
		658		1	5.20	5.28	5.79	5.42	5.44	6.00	-	5.72
				2	5.83	5.94	6.12	5.96	4.80	5.02	5.25	5.02

** BL = Brooksville Limestone; RG = River Gravel; DL = Dense Limestone.

(concrete specimen) was used in the measurement of water-saturated and oven-dried treatment responses.

The subprogram PROC MEANS within the SAS/SAT software was used to analyze the difference between the water-saturated and oven-dried conditions. The results are presented in Table 11.3. The analysis result shows the value of t = -6.79 has a significance probability of P = 0.0001. This means that there is a difference in the coefficient of linear thermal expansion of the water-saturated and oven-dried condition. Since the mean of the difference is negative (-0.39116505), the value of the coefficient of thermal expansion under oven-dry condition is significantly higher than that under saturated condition.

Table 11.4 presents the mean, standard error of the mean, and 95% confidence interval for the test results of water-saturated and oven-dried conditions. The Z statistic was used to compute the confidence intervals because the sample size is large (greater than 30). The population variance was estimated from the sample variance. A 0.95 confidence coefficient was used to determine the confidence limits presented in the table.

11.3.2 ANOVA Models

The ANOVA models used to analyze test results on the water-saturated and oven-dried laboratory concrete specimens are the same as those presented in Equations 7.1 and 7.3 in Chapter 7.

11.3.3 Results of Water-Saturated Experimental Design No.1

ANOVA was performed on the water-saturated test results from Design No. 1, which investigated the effects of aggregate type, water-cement ratio, and curing duration on the coefficient of linear thermal expansion of water-saturated laboratory concrete specimens. The analysis

Table 11.3 Result of PROC MEANS on Paired Comparison of Single Sample Groups

Variable = Coefficient of expansion of Water-Saturated Specimen Minus Coefficient of expansion of Oven-Dried Specimen

Mean = -0.39116505

Standard Deviation = 0.58454323

Standard Error of Mean = 0.05759676

T Statistic = -6.79

Significance Probability = 0.0001*

* Significant at $\alpha = 0.01$ level

Table 11.4 Mean, Standard Error of the Mean, and 95% Confidence Interval of Coefficient of Thermal Linear Expansion Results

(a) Brooksville Limestone

Condition	Moist-Curing Duration*	Mean ($x10^{-6}$/°F)	Standard Error of Mean ($x10^{-6}$/°F)	95% Confidence Interval ($x10^{-6}$/°F)
Water-Saturated	28- and 90-day	5.42	0.0439637	5.33, 5.51
Oven-Dried	28-day	5.57	0.0899910	5.39, 5.75
	90-day	5.80	0.0738908	5.66, 5.94
	28- and 90-day	5.68	0.0598284	5.56, 5.80
Water-Saturated and Oven-Dried	28-day	5.52	0.0574890	5.41, 5.63
	90-day	5.59	0.0525819	5.49, 5.69
	28- and 90-day	5.55	0.0388758	5.47, 5.63

(b) Dense Limestone

Condition	Moist-Curing Duration*	Mean ($x10^{-6}$/°F)	Standard Error of Mean ($x10^{-6}$/°F)	95% Confidence Interval ($x10^{-6}$/°F)
Water-Saturated	28- and 90-day	5.83	0.0682782	5.70, 5.96
Oven-Dried	28-day	6.14	0.0740250	5.99, 6.29
	90-day	5.83	0.1038420	5.63, 6.03
	28- and 90-day	5.99	0.0679264	5.86, 6.12
Water-Saturated and Oven-Dried	28-day	6.00	0.0625680	5.88, 6.12
	90-day	5.82	0.0719795	5.68, 5.96
	28- and 90-day	5.91	0.0487265	5.81, 6.01

* Moist-curing duration for water-saturated condition is not significant.

Table 11.4 continued

(c) River Gravel

Condition	Moist-Curing Duration*	Mean $(x10^{-6}/°F)$	Standard Error of Mean $(x10^{-6}/°F)$	95% Confidence Interval $(x10^{-6}/°F)$
Water-Saturated	28- and 90-day	6.49	0.0690387	6.35, 6.63
Oven-Dried	28-day	7.63	0.0760560	7.48, 7.78
	90-day	6.77	0.1295830	6.52, 7.02
	28- and 90-day	7.20	0.1038890	7.00, 7.40
Water-Saturated and Oven-Dried	28-day	7.12	0.1105550	6.90, 7.34
	90-day	6.58	0.0829270	6.42, 6.74
	28- and 90-day	6.85	0.0754738	6.70, 7.00

* Moist-curing duration for water-saturated condition is not significant.

results are summarized in Table 11.5. Only the effect of aggregate type is significant.

Table 11.6 presents the results of Duncan's test performed on the aggregate type at 5% alpha level. The effects of the three aggregates are significantly different from one another. River gravel produces the highest coefficient followed by dense limestone and Brooksville limestone. The mean coefficient of expansion of river gravel is about 11% and 19% higher than dense limestone and Brooksville limestone, respectively.

11.3.4 Results of Water-Saturated Experimental Design No. 5

This design investigated the effects of cement content and moist curing duration on the response variable. Table 11.7 shows the result of the ANOVA performed on the test data. The effects of the cement content and curing duration are shown to be insignificant.

11.3.5 Results of Water-Saturated Experimental Design No. 6

ANOVA was performed on the test result. The analysis result is summarized in Table 11.8. Neither the effect of the cement content nor the moist curing duration is shown to be significant.

11.3.6 Graphical Presentation of Means from Water-Saturated Test

Figures 11.1 through 11.3 illustrate the means of the coefficient of linear thermal expansion of water-saturated concrete for each of the three types of aggregates at water-cement ratios of 0.33, 0.45, and 0.53, respectively.

11.3.7 Results of Oven-Dried Experimental Design No. 1

The results of the ANOVA performed on data obtained from oven-dried experimental Design No. 1 are summarized in Table 11.9. Aggregate type, moist curing duration, and their interaction are highly significant.

Table 11.5 Results of ANOVA on Data from Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimen in Design No. 1

Source of Variation	df	SS	MS	F	P
A	2	18.40E-12	9.20E-12	34.10	0.0001**
E	2	0.84E-12	0.42E-12	1.56	0.2616
AE	4	1.43E-12	0.36E-12	1.33	0.3309
B(A*E)	9	2.43E-12	0.27E-12	-	-
D	1	0.22E-12	0.22E-12	0.51	0.4936
AD	2	0.03E-12	0.02E-12	0.04	0.9651
ED	2	0.10E-12	0.05E-12	0.12	0.8875
AED	4	1.46E-12	0.36E-12	0.85	0.5304
BD(A*E)	9	3.87E-12	0.43E-12	5.85	0.0001**
ε	67	4.93E-12	0.07E-12	-	-

R-Square = 0.858281

** Significant at α = 0.01 level.

Table 11.6 Grouping of Aggregate Type by Means of Coefficient of Linear Thermal Expansion of Water-Saturated Concrete from Duncan's Test [Design No. 1]

Alpha = 0.05 DF = 9 MSE = 0.27E-6

Aggregate Type	Mean	Grouping*
River Gravel	6.49×10^{-6}/°F	A
Dense Limestone	5.83×10^{-6}/°F	B
Brooksville Limestone	5.44×10^{-6}/°F	C

* Note: Means with different letters are significantly different.

Table 11.7 Results of ANOVA on Data from Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimen in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	0.01E-12	0.01E-12	0.01	0.9243
B(C)	2	1.75E-12	0.88E-12	-	-
D	1	0.00E-12	0.00E-12	0.02	0.8955
CD	1	0.39E-12	0.39E-12	1.74	0.3184
BD(C)	2	0.44E-12	0.22E-12	2.14	0.1606
ε	12	1.22E-12	0.10E-12	-	-

R-Square = 0.698061

Table 11.8 Results of ANOVA on Data from Coefficient of Linear Thermal Expansion Test on Water-Saturated Concrete Specimen in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	0.04E-12	0.04E-12	0.09	0.7966
B(C)	2	0.82E-12	0.41E-12	-	-
D	1	0.01E-12	0.01E-12	0.18	0.7147
CD	1	0.21E-12	0.21E-12	3.10	0.2204
BD(C)	2	0.59E-12	0.04E-12	1.65	0.2265
ε	14	0.59E-12	0.04E-12	-	-

R-Square = 0.673171

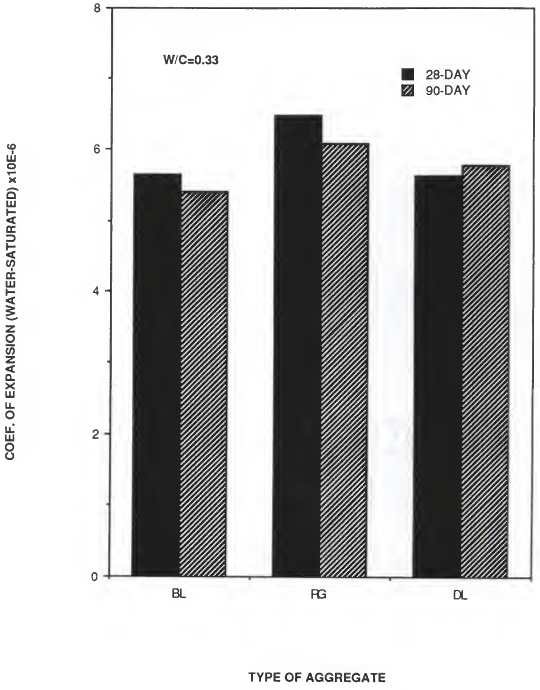

Figure 11.1 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Water-Saturated Concrete at W/C = 0.33

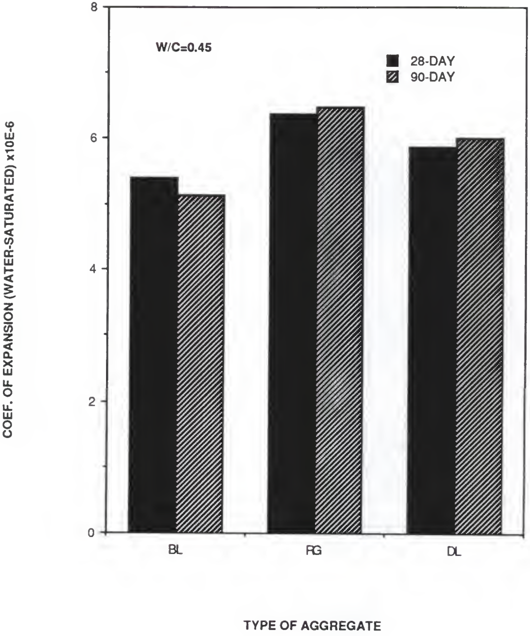

Figure 11.2 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Water-Saturated Concrete at W/C = 0.45

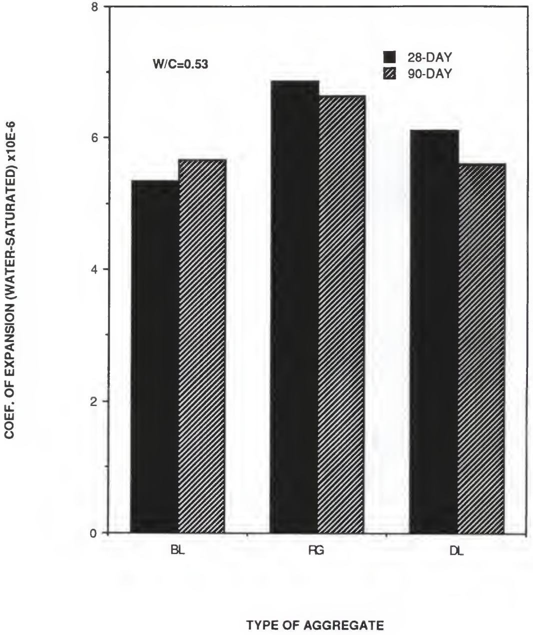

Figure 11.3 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Water-Saturated Concrete at W/C = 0.53

Table 11.9 Results of ANOVA on Data from Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens in Design No. 1

Source of Variation	df	SS	MS	F	P
A	2	43.85E-12	21.93E-12	52.23	0.0001**
E	2	0.10E-12	0.05E-12	0.12	0.8845
AE	4	4.37E-12	1.09E-12	2.60	0.1076
B(A*E)	9	3.78E-12	0.42E-12	-	-
D	1	2.75E-12	2.75E-12	11.08	0.0088**
AD	2	5.17E-12	2.59E-12	10.41	0.0046*
ED	2	0.13E-12	0.07E-12	0.26	0.7799
AED	4	1.91E-12	0.48E-12	1.92	0.1906
BD(A*E)	9	2.24E-12	0.25E-12	2.54	0.0136*
ε	72	7.04E-12	0.10E-12	-	-

R-Square = 0.901342

* Significant at $\alpha = 0.05$ level.

** Significant at $\alpha = 0.01$ level.

A comparison of means of the significant effects by Duncan multiple range test at 5% probability of error level was performed and the results summarized in Table 11.10. At 28-day moist curing duration, all the three aggregates are significantly different from each other. At age of 90-days, concrete made with Brooksville limestone and dense limestone do not show significant difference in the value of the coefficient of linear expansion. However, the river gravel produced significantly higher value than the other two aggregate types.

11.3.8 Results of Experimental Design No. 5

ANOVA was performed on the test result of Design No. 2, which studied the effects of cement content and moist curing duration given water-cement ratio of 0.53 and Brooksville limstone. The outcome of the analysis is summarized in Table 11.11. None of the two effects is s nificant.

11.3.9 Results of Experimental Design No. 6

The purpose of this design is the same as that of Design No. 2 except that the water-cement ratio is 0.45. The result was analyzed using ANOVA procedure in SAS/STAT software. Table 11.12 summarizes the analysis result. All the effects are insignificant.

11.3.10 Graphical Presentation of Means from Oven-Dried Test

The means of the coefficient of linear thermal expansion of oven-dried concrete for each type of aggregate at water-cement ratios of 0.33, 0.45, and 0.53 are plotted in Figures 11.4 through 11.6, respectively.

Table 11.10 Grouping of Aggregate Type by Means of Coefficient of Linear Thermal Expansion of Oven-Dried Concrete from Duncan's Test [Design No. 1]

Duration = 28-day: Alpha = 0.05 DF = 9 MSE = 0.42E-6

Duration = 90-day: Alpha = 0.05 DF = 9 MSE = 0.39E-6

Moist Curing Duration	Aggregate Type	Mean	Grouping*
28 - day	River Gravel	7.63×10^{-6}/°F	A
	Dense Limestone	6.14×10^{-6}/°F	B
	Brooksville Limestone	5.64×10^{-6}/°F	C
90 - day	River Gravel	6.77×10^{-6}/°F	A
	Brooksville Limestone	5.85×10^{-6}/°F	B
	Dense Limestone	5.83×10^{-6}/°F	B

* Note: Means at each moist curing duration with the same letter are not significantly different.

Table 11.11 Results of ANOVA on Data from Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	0.26E-12	0.26E-12	0.30	0.6401
B(C)	2	1.72E-12	0.86E-12	-	-
D	1	1.49E-12	1.49E-12	2.56	0.2505
CD	1	0.08E-12	0.08E-12	0.14	0.7406
BD(C)	2	1.16E-12	0.58E-12	5.43	0.0179*
ε	14	1.50E-12	0.11E-12	-	-

R-Square = 0.751944

* Significant at $\alpha = 0.05$ level.

Table 11.12 Results of ANOVA on Data from Coefficient of Linear Thermal Expansion Test on Oven-Dried Concrete Specimens in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	0.29E-12	0.29E-12	0.28	0.6471
B(C)	2	2.01E-12	1.00E-12	-	-
D	1	0.00E-12	0.00E-12	0.00	0.9799
CD	1	0.55E-12	0.55E-12	0.79	0.4681
BD(C)	2	1.39E-12	0.69E-12	7.81	0.0047**
ε	15	1.33E-12	0.09E-12	-	-

R-Square = 0.767649

** Significant at $\alpha = 0.01$ level.

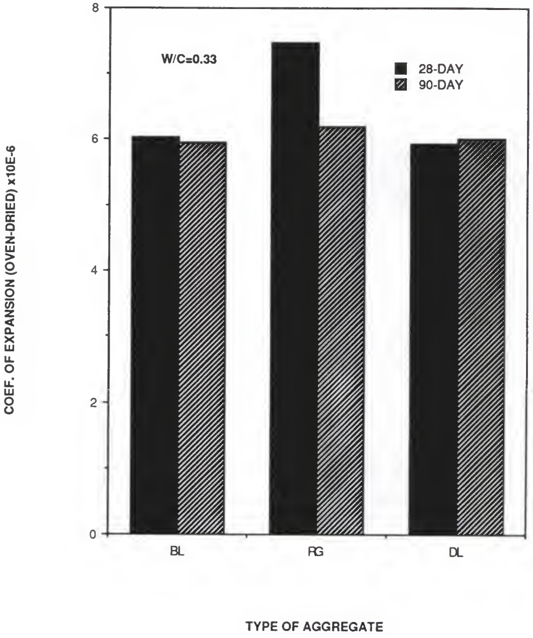

Figure 11.4 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Oven-Dried Concrete at W/C = 0.33

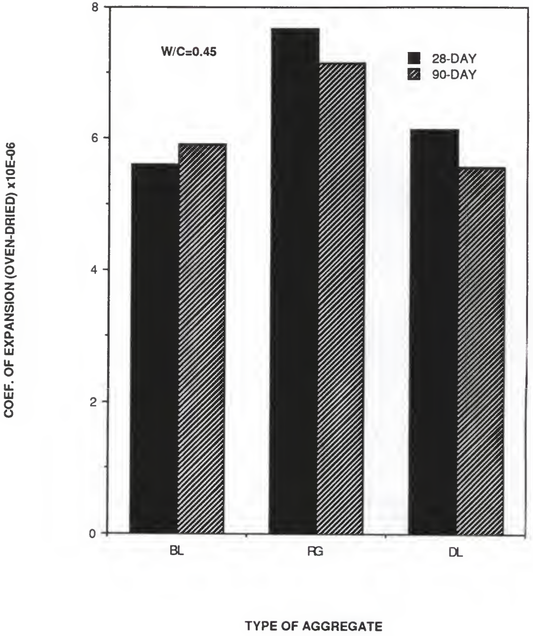

Figure 11.5 Influence of Aggregate Type and Moist Curing Duration on Coefficient of Expansion of Oven-Dried Concrete at W/C = 0.45

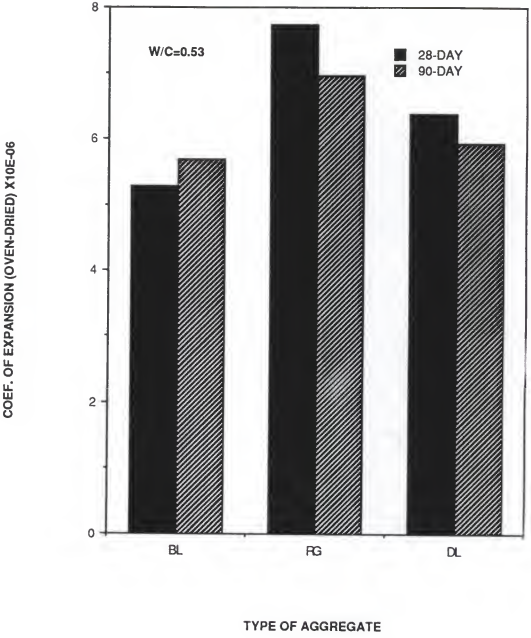

Figure 11.6 Influence of Aggregate Type and Moist-Curing Duration on Coefficient of Expansion of Oven-Dried Concrete at W/C = 0.53

11.4 Summary of Findings

The findings from the coefficient of linear thermal expansion test are

1. Aggregate type has some effect on the coefficient of linear thermal expansion of water-saturated and oven-dried concrete. At water-saturated condition, all the three aggregates show significant difference from each other. The river gravel has the highest coefficient of expansion and Brooksville limestone the least. Under the oven-dried condition, all the three aggregates are significantly different from one another at 28-day moist-cured age. The river gravel produces the highest coefficient followed by dense limestone and Brooksville limestone has the least. At 90-day moist-cured age, the Brooksville limestone and dense limestone do not show any significant difference from each other. The river gravel, however, gives significantly higher coefficient of thermal expansion than the other two aggregates.
2. The water-cement ratio and the cement content did not show any effect on the coefficient of linear thermal expansion.
3. The moist-curing duration does affect the coefficient of linear thermal expansion in oven-dried condition but not in water-saturated condition. The coefficient of thermal expansion of concrete in oven-dried condition is signficantly higher at 28-day moist curing than that at 90-day moist curing.

CHAPTER 12

COEFFICIENT OF MOISTURE EXPANSION OF LABORATORY CONCRETE SPECIMENS

12.1 Introduction

The effects of moisture on laboratory concrete were determined by measuring the length change of the concrete specimens from oven-dried condition to various degrees of saturation of the concrete. The length of the test specimens were measured at the oven-dried condition, fully saturated condition and partially saturated condition.

All readings were recorded at 77°F air temperature.. Readings were corrected accordingly in cases of ambient temperature deviations.

This chapter presents the method of calculation and results of measurement of length change due to moisture effects on laboratory concrete specimens.

12.2 Calculation of Coefficient of Moisture Expansion

The coefficient of moisture expansion is defined as the length change per unit length of a concrete as the moisture content increases from oven-dried to fully saturated condition. It is calculated as

$$\text{Coefficient of Moisture Expansion} = \frac{L_{sat} - L_{oven}}{L_{oven}} \qquad (12.1)$$

where:

L_{sat} = Length at water-saturated condition

L_{oven} = Length at oven-dried condition

Table 12.1 summarizes the results of moisture expansion test.

Table 12.1 Results of Moisture Expansion of Concrete Specimens

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Maximum Size=3/8")	Replicate	Coefficient of Moisture Expansion (x 10E-4)									
					28-Day Moist Curing					90-Day Moist Curing				
					Specimens			Average		Specimens			Average	
					1	2	3			1	2	3		
2	0.53	508	BL	1	-	-	-	-		2.61	2.62	2.99	2.74	(6.6)+
				2	3.48	3.54	4.40	3.81	(7.4)	2.67	2.95	-	2.81	(7.7)
(1a)			RG	1	3.97	4.13	4.14	4.08	(7.3)	2.83	3.29	3.48	3.20	(7.4)
				2	4.08	4.18	4.45	4.24	(7.6)	0.94	2.85	8.73	4.17	(5.3)
			DL	1	-	-	-	-	-	-	-	-	-	-
				2	2.13	2.38	2.57	2.36	(6.1)	1.97	2.17	2.24	2.13	(6.0)
3	0.45	564	BL	1	3.67	3.67	3.84	3.73	(6.9)	3.41	3.51	3.58	3.50	(7.0)
				2	2.85	3.96	4.17	3.66	(6.2)	1.95	2.10	2.94	2.33	(6.6)
(1b)			RG	1	3.84	3.85	5.02	4.24	(6.4)	2.46	2.50	2.84	2.60	(5.6)
				2	3.84	3.90	4.02	3.92	(6.3)	1.57	1.63	1.73	1.64	(4.6)
			DL	1	3.21	3.32	3.38	3.30	(6.1)	2.13	2.13	2.50	2.25	(5.4)
				2	1.80	1.87	1.97	1.88	(6.0)	2.27	2.54	2.67	2.49	(5.5)
4	0.33	752	BL	1	3.88	3.74	3.79	3.80	(7.1)	3.85	3.86	4.07	3.93	(7.2)
				2	4.04	4.13	4.63	4.27	(7.7)	3.02	3.35	3.43	3.27	(6.9)
(1c)			RG	1	4.65	4.93	4.97	4.85	(5.7)	2.55	2.62	2.64	2.60	(3.7)
				2	3.33	3.94	4.06	3.78	(5.2)	2.21	2.46	2.52	2.40	(4.1)
			DL	[illegible]	2.18	2.58	[illegible]	2.72	(5.4)	1.	.49	1.61	1.51	(4.3)
				[illegible]	1.49	1.62	[illegible]	1.71	(4.2)	0.	.46	2.29	1.51	(3.6)

Table 12.1 continued

Design No.*	W/C	Cement Content (lb/cy)	Aggregate Type ** (Maximum Size=3/8")	Replicate	Coefficient of Moisture Expansion (x 10E-4)									
					28-Day Moist Curing					90-Day Moist Curing				
					Specimens			Average		Specimens			Average	
					1	2	3			1	2	3		
5	0.53	508	BL	1	-	-	-	-		2.61	2.62	2.99	2.74	(6.6)
				2	3.48	3.54	4.40	3.81	(7.4)	2.67	2.95	-	2.81	(7.7)
		564	BL	1	0.29	1.30	7.96	3.18	(3.6)	2.85	-	-	2.85	(2.9)
				2	2.95	3.08	4.26	3.43	(8.9)	3.54	3.63	3.75	3.64	(9.1)
6	0.45	564	BL	1	3.67	3.67	3.84	3.73	(6.9)	3.41	3.51	3.58	3.50	(7.0)
				2	2.85	3.96	4.17	3.66	(6.2)	1.95	2.10	2.94	2.33	(6.6)
		658	BL	1	-	-	-	-		2.32	3.39	3.56	3.09	(7.3)
				2	3.69	3.75	3.77	3.74	(8.9)	3.22	3.36	3.41	3.33	(8.6)
7	0.45	658	BL	1 2	(Same as in Design No. 6)									
	0.38	658	BL	1	2.76	2.95	3.52	3.08	(6.0)	2.28	2.40	2.74	2.47	(6.2)
				2	3.08	3.67	4.39	3.71	(5.4)	2.88	2.97	3.56	3.14	(5.7)

* Design No. 1 data is the same as that for Designs 2-4 combined.

** BL = Brooksville Limestone; RG = River Gravel; DL = Dense Limestone

+ Absorbed moisture (% of oven-dried weight)

12.3 Analysis of Results

12.3.1 Results of Experimental Design No. 1

The objective was to study the effects of aggregate type, water-cement ratio, and curing duration on the moisture expansion of concrete.

ANOVA was performed on the moisture expansion test data from Design No. 1 using the ANOVA model presented in Equation 7.1. The ANOVA results are summarized in Table 12.2.

The aggregate type and curing duration main effects are found to be significant at 1% probability of error level. The moisture expansion of concrete was found to decrease with age of moist-curing from a mean of 3.52E-04 for 28-day to 2.65E-04 for 90-day. Table 12.3 shows the results of Duncan's multiple comparison range test. River gravel and Brooksville limestone mean moisture expansion coefficient are not significantly different from each other and are about 58% higher than that of the dense limestone.

Since Design No. 1 includes Design Nos. 2 through 4, separate analyses of data from Design Nos. 2, 3 and 4 were not necessary.

12.3.2 Results of Experimental Design No. 5

The ANOVA results for Design No. 5, which studied the effects of cement content and moist-curing duration on the coefficient of moisture expansion using a fixed water-cement ratio of 0.53, Brooksville limestone, and cement content of 508 and 564 lb. per cubic yard, are presented in Table 12.4. The model used in the analysis is as expressed by Equation 7.3. The effects of the cement content and curing duration were found not to be significant.

Table 12.2 Results of ANOVA on Data from Moisture Expansion of Concrete Specimens in Design No. 3

Source of Variation	df	SS	MS	F	P
A	2	25.44E-08	12.72E-08	15.93	0.0016**
E	2	0.34E-08	0.17E-08	0.22	0.8108
AE	4	7.46E-08	1.87E-08	2.34	0.1428
B(A*E)	8	6.39E-08	0.80E-08	--	-
D	1	18.09E-08	18.09E-08	20.83	0.0026**
AD	2	6.41E-08	3.21E-08	3.69	0.0805
ED	2	0.46E-08	0.23E-08	0.26	0.7760
AED	4	3.02E-08	0.76E-08	0.87	0.5271
BD(A*E)	7	6.08E-08	0.87E-08	1.42	0.2130
ε	65	39.79E-08	0.61E-08	--	-

R-Square = 0.678060

** Significant at $\alpha = 0.01$ level.

Table 12.3 Grouping of Aggregate Type by Means of Coefficient of Moisture Expansion from Duncan's Test [Design No. 1]

Alpha = 0.05 DF = 8 MSE = 0.80E-4

Aggregate Type	Mean	Grouping*
River Gravel	3.48×10^{-4}	A
Brooksville Limestone	3.46×10^{-4}	A
Dense Limestone	2.19×10^{-4}	B

* NOTE: Means with the same letter are not significantly different.

Table 12.4 Results of ANOVA on Data from Moisture Expansion of Concrete in Design No. 5

Source of Variation	df	SS	MS	F	P
C	1	0.13E-08	0.13E-08	0.50	0.5540
B(C)	2	0.54E-08	0.54E-08	--	--
D	1	0.44E-08	0.44E-08	3.00	0.3334
CD	1	0.66E-08	0.66E-08	4.44	0.2820
BD(C)	1	0.15E-08	0.15E-08	0.04	0.8367
ε	11	35.46E-08	3.31E-08	--	--

R-Square = 0.071703

12.3.3 Results of Experimental Design No. 6

ANOVA was performed on the data in Design No. 6, which studied the effects of cement content (564 and 658 lb. per cubic yard) and moist-curing duration given a water-cement ratio of 0.45 and Brooksville limestone. The results of ANOVA are summarized in Table 12.5.

The analysis results shows that the effects of cement content and moist-curing duration are not significant.

12.3.4 Results of Experimental Design No. 7

The results of analysis of variance performed on the data in Design No. 7, which studied the effects of water-cement ratio and moist-curing duration on the coefficient of moisture expansion using Brooksville limestone and a fixed cement content of 658 lb/cy, are summarized in Table 12.6.

The effect of cement content is found to be insignificant. However, the effect of the moist-curing duration is shown to be significant. At 28-day, the coefficient of moisture expansion is about 17% higher than at 90-day (3.51E-04 versus 3.01E-04).

12.3.5 Graphical Presentation of Means

The means of the coefficient of moisture expansion for each aggregate type at water-cement ratios of 0.33, 0.45, and 0.53 are respectively shown in Figures 12.1 through 12.3.

12.4 Summary of Findings

The following are findings from the coefficient of moisture expansion test:

1. Aggregate type has some effect on the coefficient of moisture expansion of concrete. Concrete made with river gravel and

Table 12.5 Results of ANOVA on Data from Moisture Expansion of Concrete in Design No. 6

Source of Variation	df	SS	MS	F	P
C	1	0.10E-08	0.10E-08	0.17	0.7205
B(C)	2	1.23E-08	0.61E-08	--	--
D	1	1.93E-08	1.93E-08	2.11	0.3838
CD	1	0.14E-08	0.14E-08	0.15	0.7638
BD(C)	1	0.91E-08	0.91E-08	5.04	0.0414*
ε	14	2.54E-08	0.18E-08		

R-Square = 0.642233

* Significant at $\alpha = 0.05$ level.

Table 12.6 Results of ANOVA on Data from Moisture Expansion of Concrete in Design No. 7

Source of Variation	df	SS	MS	F	P
C	1	0.59E-08	0.59E-08	0.87	0.4503
B(C)	2	1.35E-08	0.67E-08	--	--
D	1	1.26E-08	1.26E-08	2360.17	0.0131*
CD	1	0.03E-08	0.03E-08	63.02	0.0798
BD(C)	1	5.33E-12	5.33E-12	0.00	0.9571
ε	14	2.49E-08	0.18E-08	--	--

R-Square = 0.575573

* Significant at $\alpha = 0.05$ level.

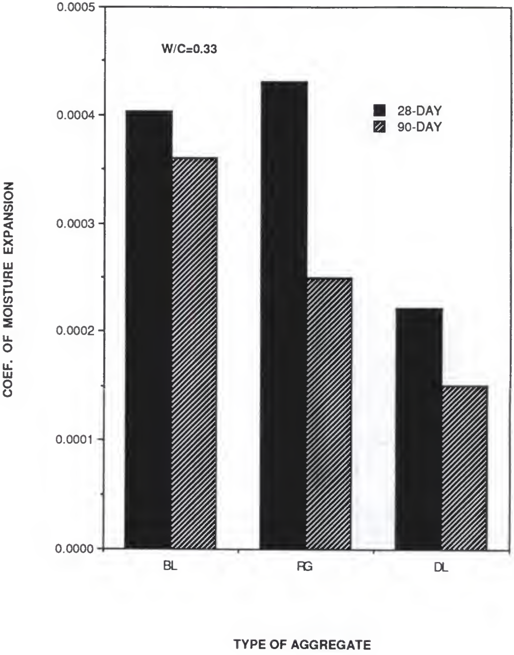

Figure 12.1 Influence of Aggregate Type and Moist-Curing Duration on the Coefficient of Moisture Expansion of Concrete at W/C = 0.33

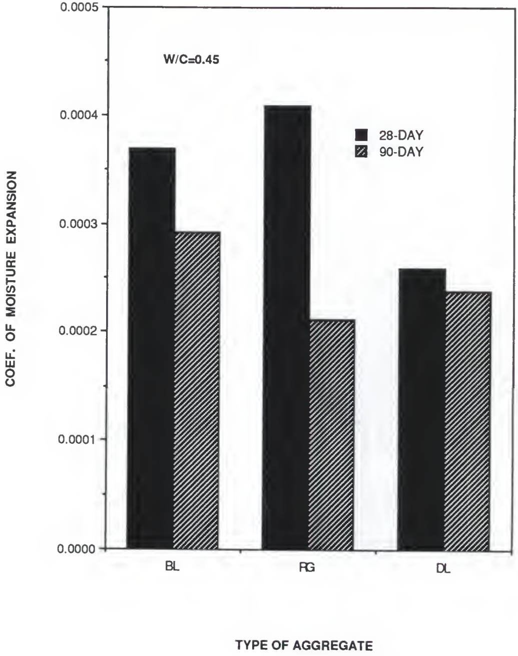

Figure 12.2 Influence of Aggregate Type and Moist-Curing Duration on the Coefficient of Moisture Expansion of Concrete at W/C = 0.45

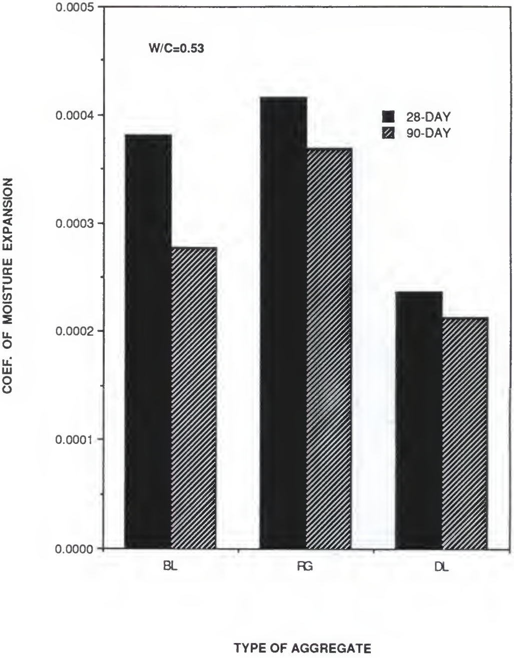

Figure 12.3 Influence of Aggregate Type and Moist-Curing Duration on the Coefficient of Moisture Expansion of Concrete at W/C = 0.53

Brooksville limestone have average coefficients of moisture expansion of 3.48E-4 and 3.46E-4, while concrete made with dense limestone has an average coefficient of moisture expansion of 2.19E-4.

2. The moist-curing duration has a significant effect on the coefficient of moisture expansion. The coefficient of moisture expansion generally decreases as the moist-curing duration increases.
3. The water-cement ratio and cement content have no significant effect on the coefficient of moisture expansion of concrete.

CHAPTER 13
RESULTS OF IN-SERVICE CONCRETE STUDY

13.1 Introduction

Concrete core samples obtained from three existing concrete pavement highways in Florida were tested. The highways are I-10, I-75, and U.S. 41 (Econocrete Test Road). The locations from which the concrete samples were obtained are presented in Table 13.1.

The tests performed were compressive strength, splitting tensile strength, modulus of elasticity, coefficient of linear thermal expansion, and coefficient of moisture expansion.

This chapter presents the results of the study on in-service concrete.

13.2 Compressive Strength Test Results

Eleven concrete cores from Sites 2, 3, 5, and 6 were used in this test. The heights of the concrete cores after preparation ranged from 9 inches for Sites 2 and 3, to 11.50 inches for Sites 5 and 6. The diameter of the cores was approximately 5 11/16 inches. The test and compressive strength computation were performed according to ASTM Standard Test Method C39-83b.

The results of the compressive strength test on the in-service concrete are presented in Table 13.2. Test results show that the compressive strength of the four sites range from 5,000 psi to 6,000 psi. Values of two defective cores from Site 3 were not used in averaging.

Table 13.1 Sites of In-Service Concrete Pavement Study

Highway	Site No.	County	Direction	Milepost	Approx. Core Height
I-75	1	Sarasota	Southbound	212.56 (Federal)	9 inches
	2	Sarasota	Southbound	202.50 (Federal)	9 inc
	3	Manatee	Southbound	223.80 (Federal)	9 inches
	4	Manatee	Southbound	229.80 (Federal)	9 inches
	5	Hillsborough	Northbound	21.30 (County)	12-13 inches
	6	Hillsborough	Northbound	24.50 (County)	12-13 inches
U.S. 41 (Econocrete Test Road)	7	Charlotte	Southbound	Station 175+00	12-13 inches (Composite)
	8	Charlotte	Southbound	Station 41 + 00	12-13 inches (Composite)
	9	Charlotte	Southbound	Station 129+00	12-13 inches (Composite)
I-10	10	Leon	Westbound	212.20 (Federal)	10 inches
	11	Jefferson	Westbound	231.00 (Federal)	10 inches

Table 13.2 Compressive Strength of In-Service Pavement Concrete

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Compressive Strength (psi)	
					per core	per site
I-75 (Southbound)	202.5 (F)	2	1	3	5834	6008
			3	2	6181	
	223.8 (F)	3	1	2	1989**	5017
			2	3	5017	
			3	2	2062**	
I-75 (Northbound)	21.3 (C)	5	2	3	5629	5939
			4	3	5869	
			5	1	5833	
				2	6424	
	24.5 (C)	6	3	2	5755	5627
			4	1	5499	

* F = Federal milepost

C = County milepost

** = Defects in core samples. Values not used in averaging.

According to the 1986 Florida Department of Transportation Standard Specifications for Road and Bridge Construction [40], a Class I concrete used for concrete pavement is required to have a minimum 28-day compressive strength of 3,000 psi. Although the test results are not for 28-day age, it appears that the strength of the concrete has exceeded the minimum requirement of the FDOT specifications.

13.3 Splitting Tensile Strength Test Results

Seventy Seven (77) concrete samples obtained from Sites 1 through were tested according to ASTM C496-71. The length of the prepared samples measured between 5 3/4 inches for Site 1 and 11 1/2 inches for Sites 5 and 6. The diameter of the samples was approximately 5 11/16 inches.

Table 13.3 shows the results of the splitting tensile strength tes performed on the in-service concrete samples. Test results for the I-7 concrete pavement range from 400 to 500 psi. These values are about 8 percent of the compressive strength. Generally, the splitting tensile strength values are about 10 percent of the compressive strength. The Site 5 shoulder core samples yielded a relatively higher tensile strength than the slab cores.

The splitting tensile strengths of the econocrete samples from the Econocrete Test Road range from about 170 to 320 psi. On the average, splitting tensile strengths of the econocrete samples are about half of those of the concrete samples from I-75 highway.

Table 13.3 Mean Splitting Tensile Strength of In-Service Pavement Concrete

Highway	Milepost	Site	Slab	Core	Splitting Tensile Strength (psi)	
(Direction)	(F/C)*				per core	per site
I-75	212.56	1	1	1	449	432
				2	459	
(Southbound)	(F)			3	470	
			3	1	461	
				2	455	
				3	473	
			4	1	453	
				2	362	
				3	384	
			5	1	432	
				2	396	
				3	394	
			Shoulder	1	590	528
				3	510	
				4	484	
				5	528	
	202.50	2	1	1	432	448
	(F)			2	315	
			2	1	443	
				2	527	
				3	442	
			3	3	526	
			Shoulder	3	438	394
				3	350	
	223.80	3	1	1	489	457
	(F)			3	486	
			2	1	473	
				2	412	
			3	1	471	
				3	424	

Table 13.3 continued

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Splitting Tensile Strength (psi) per core	per site
			4	1	455	
				2	443	
				3	459	----
			Shoulder	1	312	343
				3	374	
	229.80	4	2	1	386	407
				2	442	
				3	400	
			3	1	357	
				2	398	
				3	387	
			4	1	425	
				2	430	
				3	438	
I-75 (Northbound)	21.30 (C)	5	1	1	500	493
				2	547	
				3	496	
			2	1	383	
				2	413	
			4	1	516	
				2	505	
			5	3	583	----
			Shoulder	1	516	578
				2	628	
				4	579	
				5	588	
	24.50 (C)	6	1	1	404	503
				2	596	
				3	577	
			2	1	521	
				2	498	
				3	475	

Table 13.3 continued

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Splitting Tensile Strength (psi) per core	Splitting Tensile Strength (psi) per site
			3	1	539	503
				3	459	
			4	2	478	
			5	2	479	
U.S. 41 (Southbound)	Station 175+00	7	1	1	256	284
				3	320	
			3	1	270	
				2	291	
	Station 41+00	8		12	203	205
				13	189	
				14	224	
				15	204	
	Station 129+00	9	3	3	181	188
			5	2	173	
				3	211	

* F = Federal milepost
C = County milepost

13.4 Static Modulus of Elasticity Test Results

Six concrete core samples from Sites 2, 5, and 6 were tested according to ASTM C469-83.

The test results are summarized in Table 13.4. The elastic moduli range from 4.25×10^6 to 4.82×10^6 psi.

Table 13.5 presents the comparison of the measured elastic moduli and the estimated values based on the ACI prediction equation using an assumed unit weight of 145 lb/ft^3. The test data and the computed values are generally in agreement.

13.5 Results of Linear Thermal Expansion of In-Service Concrete

Thirty five (35) core samples from I-10, I-75, and U.S. 41 (Econocrete Test Road) were tested under water-saturated and oven-dried conditions to determine the coefficient of linear thermal expansion. The test results of the water-saturated and oven-dried coefficient of linear thermal expansion of the in-service concrete are presented in Tables 13.6 and 13.7, respectively. At the water-saturated condition, the coefficients of linear thermal expansion of the concrete from Sites 2 (I-75) and 8 (U.S. 41) are significantly higher than those from the other sites. Also, the coefficient of thermal expansion of the core samples from the shoulder of Site 5 is significantly higher than the average value of the pavement concrete samples from the same site. The mean coefficient of linear thermal expansion per site under water-saturated condition range from 5.52×10^{-6}in/in/°F for Site 1 to 9.83×10^{-6}in/in/°F for Site 8.

Under the oven-dried condition, the mean coefficient of linear thermal expansion per site range from 3.39×10^{-6} for Site 6 to 7.22

Table 13.4 Modulus of Elasticity of In-Service Pavement Concrete

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Modulus of Elasticity (psi)	
					per core	per site
I-75 (Southbound)	202.50 (F)	2	2	3	4.67×10^6	4.63×10^6
			3	3	4.58×10^6	
I-75 (Northbound)	21.30 (C)	5	2	1	4.92×10^6	4.82×10^6
			5	3	4.72×10^6	
	24.50 (C)	6	2	2	4.43×10^6	4.25×10^6
			4	2	4.06×10^6	

* F = Federal milepost

C = County milepost

Table 13.5 Comparison of Measured and Estimated Static Moduli of Elasticity of Concrete

Site	Mean Compressive Strength	Test E_c (psi)	ACI Predicted E_c (psi) (Assume $w = 145\ lb/ft^3$)
2	6008	4.63×10^6	4.47×10^6
5	5939	4.82×10^6	4.44×10^6
6	5627	4.25×10^6	4.32×10^6

Table 13.6 Results of Coefficient of Linear Thermal Expansion Test on Water-Saturated In-Service Concrete

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Water-Saturated Coefficient of Linear Thermal Expansion (x 10^{-6}/°F)	
					per core	per site
I-75 (Southbound)	212.56 (F)	1	2	1	5.89	5.52
				2	6.13	
				3	4.55	
	202.50 (F)	2	3	1	9.64	8.94
			5	2	8.23	
				3	8.95	
	223.80 (F)	3	5	2	6.83	6.55
				3	6.27	
	229.80 (F)	4	1	1	7.37	6.18
				2	6.04	
				3	4.41	
			5	1	6.91	
I-75 (Northbound)	21.30 (C)	5	3	1	5.60	5.84
				2	6.59	
				3	5.34	
			Shoulder	5	7.13	7.13
	24.50 (C)	6	5	1	7.28	6.21
				3	5.13	
U.S. 41 (Southbound)	Station 175+00	7	2	1	6.77	6.63
				2	6.82	
				3	6.31	
	Station 41+00	8		9	9.84	9.83
				11	9.82	
	Station 129+00	9	4	3	6.18	6.18

Table 13.6 continued

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Water-Saturated Coefficient of Linear Thermal Expansion (x 10^{-6}/°F)	
					per core	per site
I-10 (Westbound)	212.20 (F)	10		4	5.75	6.91
				5	8.08	
	231.00 (F)	11		1	6.15	6.21
				4	4.42	
				5	6.18	
				7	6.36	
				8	6.07	
				9	7.40	
				10	6.53	
				11	6.04	
				12	6.71	

* F = Federal milepost

C = County milepost

Table 13.7 Results of Coefficient of Linear Thermal Expansion Test on Oven-Dried In-Service Concrete

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Oven-Dried Coefficient of Linear Thermal Expansion x 10^{-6}/°F)	
					per core	per site
I-75 (Southbound)	212.56 (F)	1	2	1	4.88	4.31
				2	5.10	
				3	2.94	
	202.50 (F)	2	3	1	7.61	7.22
			5	2	6.86	
				3	7.19	
	223.80 (F)	3	5	2	5.67	5.07
				3	4.47	
	229.80 (F)	4	1	1	3.42	3.88
				2	4.08	
				3	3.85	
			5	1	3.91	
				2	3.43	
				3	4.57	
I-75 (Northbound)	21.30 (C)	5	3	1	5.11	5.22
				2	5.35	
				3	5.19	
			Shoulder	5	5.05	5.05
	24.50 (C)	6	4	3	3.59	3.39
			5	1	3.53	
				3	3.04	
U.S. 41 (Southbound)	Station 175+00	7	2	1	4.32	4.54
				2	4.52	
				3	4.77	
	Station 41+00	8		9	5.76	5.70
				11	5.63	
	Station 129+00	9	4	3	4.99	

Table 13.7 continued

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Oven-Dried Coefficient of Linear Thermal Expansion (x 10^{-6}/°F) per core	per site
I-10 (Westbound)	212.20 (F)	10		1	3.87	3.97
				2	4.89	
				3	2.88	
				4	4.53	
				5	4.48	
				6	2.69	
				7	3.37	
				9	5.11	
				11	4.66	
				12	4.02	
				13	2.50	
				14	3.76	
				15	4.83	
	231.00 (F)			1	3.84	3.52
				2	3.82	
				3	3.95	
				4	4.26	
				5	4.07	
				6	2.01	
				7	3.10	
				8	4.32	
				10	3.80	
				11	5.08	
				12	4.22	
				13	2.55	
				14	2.11	
				15	2.15	

* F = Federal milepost

C = County milepost

x 10^{-6}in/in/°F for Site 2. The concrete samples from Site 2 registered high mean coefficient of linear thermal expansion for both water-saturated and oven-dried conditions. The average coefficient for I-10 concrete core samples is about 3.75 x 10^{-6}in/in/°F, which is lower than all the other highways.

The significance of the difference between the water-saturated and oven-dried coefficient of linear thermal expansion was tested by means of student T test using the PROC MEANS procedure of the SAS/STAT software. The analysis results are summarized in Table 13.8. It indicate that the coefficient of linear thermal expansion at the water-saturated condition is significantly higher than that at the oven-dried condition.

13.6 Results of Moisture Expansion of In-Service Concrete

The effects of moisture on the in-service concrete were determined by measuring the length change of the specimens at the oven-dried, fu and partial saturation conditions. The coefficient of moisture expansion was calculated using the formula presented as Equation 12.1.

The results of measurement of length change caused by the effects of moisture on the in-service concrete are summarized in Table 13.9. The specimens from Site 6 in I-75 (Northbound) showed the least amount of expansion due to moisture. With the exception of specimens from Site 7, the econocrete samples from U.S. 41 Econocrete Test Road (Southboun expanded the most due to moisture. The range of the coefficient of moisture expansion for the in-service concrete range from 0.72 x 10^{-4}in/in for concrete from I-75 to 9.59 x 10^{-4}in/in for the econocrete from U.S.

Table 13.8 Results of T Test on the Difference Between the Coefficient of Thermal Expansion at Water-Saturated and Oven-Dried Conditions

Variable = Coefficient of expansion of water-saturated specimen minus coefficient of expansion of oven-dried specimen.

Highway (Direction)	Mean	Standard Deviation	Standard Error of Mean	T	PR > T
I-75 (Southbound)	1.77	0.9302	0.2685	6.59	0.0001**
I-75 (Northbound)	1.63	1.3077	0.5339	3.06	0.0281*
U.S. 41 (Southbound)	2.63	1.2601	0.5144	5.10	0.0038**
I-10 (Westbound)	2.06	1.0610	0.3355	6.14	0.0002**
All	1.98	1.1002	0.1887	10.50	0.0001**

* Significant at $\alpha = 0.05$ level.

** Significant at $\alpha = 0.01$ level.

Table 13.9 Results of Moisture Expansion Test on In-Service Concrete

Highway (Direction)	Milepost (F/C)*	Site	Slab	Core	Coefficient of Moisture Expansion (x 10^{-4})	
					per core	per site
I-75 (Southbound)	212.56 (F)	1	2	1	1.64	1.67 (6.0)+
				2	1.70	
	202.50 (F)	2	3	1	2.03	1.68 (3.8)
			5	2	1.35	
				3	1.66	
	223.80 (F)	3	5	2	2.12	1.72 (5.9)
				3	1.31	
	229.80 (F)	4	1	1	1.39	1.77 (5.3)
				2	2.10	
				3	1.65	
			5	1	1.95	
				2	1.50	
				3	2.03	
I-75	21.30 (C)	5	3	1	1.36	1.22 (5.5
				2	1.07	
			Shoulder	5	1.31	1.31 (5.0)
	24.50 (C)	6	4	3	0.70	0.72 (6.2)
			5	1	0.90	
				3	0.57	
U.S.41	Station 175+00	7	2	1	0.75	0.86 (9.0)
				2	1.08	
				3	0.75	
	Station 41+00	8		9	3.53	4.22 (10.2
				11	4.90	
	Station 129+00	9	4	3	9.59	9.59 (10.6)

* F = Federal milepost

C = County milepost

+ Absorbed moisture (% of oven-dried weight)

41 Econocrete Test Road. The average expansion caused by moisture of the concrete samples from I-75 (Southbound) is 1.71×10^{-4}in/in.

13.7 Graphical Representation of Means

Figures 13.1 through 13.3 show the graphical presentation of the means per site of, respectively, compressive, splitting tensile, and modulus of elasticity of the in-service concrete core samples. The per site mean values for water-saturated, and oven-dried coefficient of linear thermal expansion are presented graphically in Figures 13.4 and 13.5. Finally, Figure 13.6 is a graphical representation of the means of the coefficient of moisture expansion.

13.8 Summary of Findings

The following are observations from the study of in-service concrete specimens:

1. The compressive strengths of the concrete samples from the existing concrete pavements in Florida exceed the FDOT compressive strength requirement.
2. The splitting tensile strengths of the econocrete samples obtained from U.S. 41 Econocrete Test Road averaged about 226 psi and are generally about 50% of the concrete samples from the other pavements. For the field concrete tested, the splitting tensile strengths are about 8% of the compressive strengths.
3. The mean modulus of elasticity of the field concrete samples tested is 4.57×10^6 psi.
4. The coefficient of linear thermal expansion for the in-service concrete under oven-dried and water-saturated conditions are

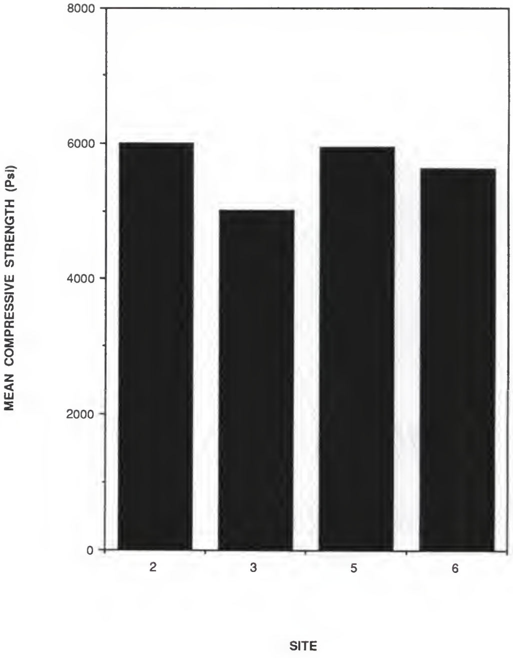

Figure 13.1 Mean Compressive Strength of In-Service Concrete Pavement

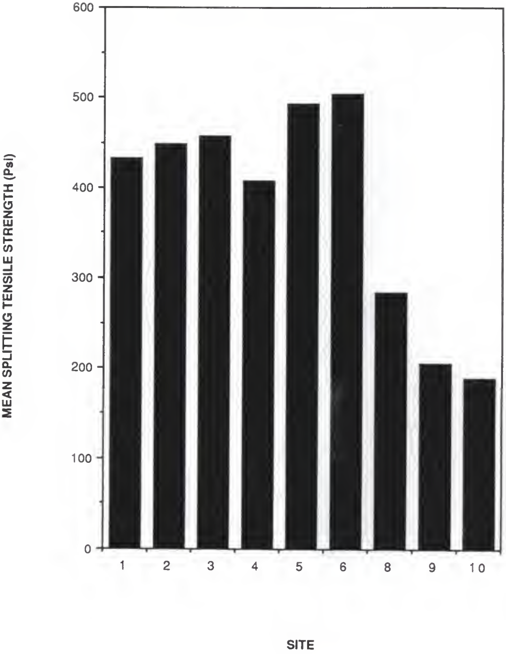

Figure 13.2 Mean Splitting Tensile Strength of In-Service Concrete Pavement

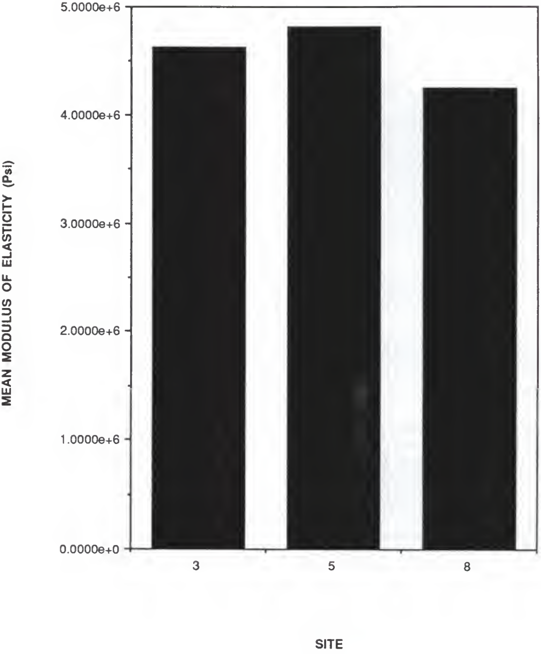

Figure 13.3 Mean Modulus of Elasticity of In-Service Concrete Pavement

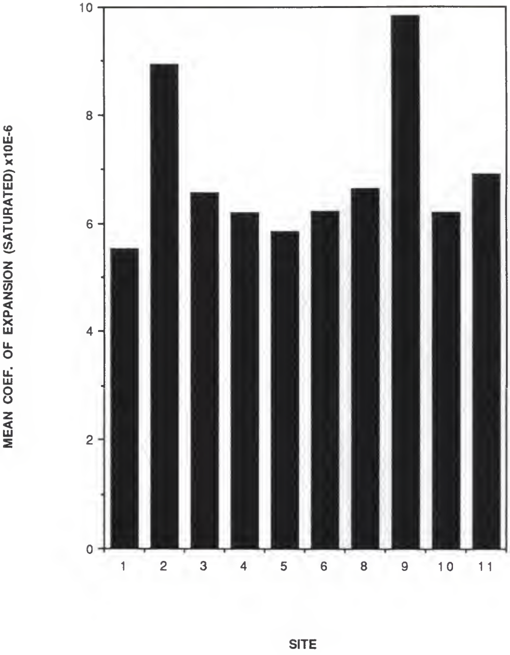

Figure 13.4 Mean Water-Saturated Coefficient of Linear Thermal Expansion of In-Service Concrete Pavement

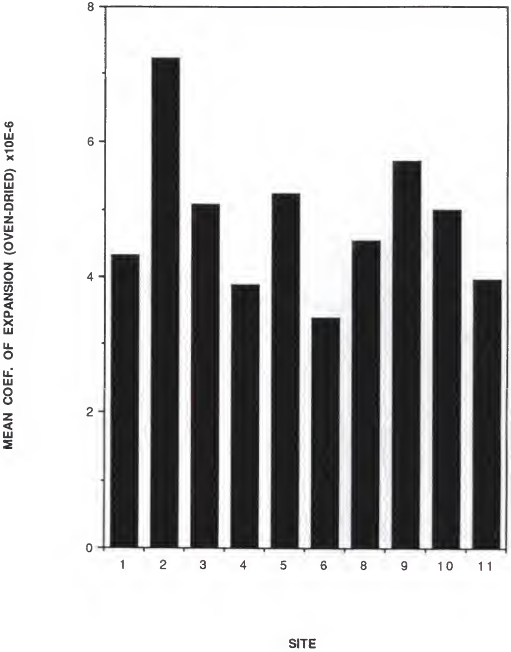

Figure 13.5 Mean Oven-Dried Coefficient of Linear Thermal Expansion of In-Service Concrete Pavement

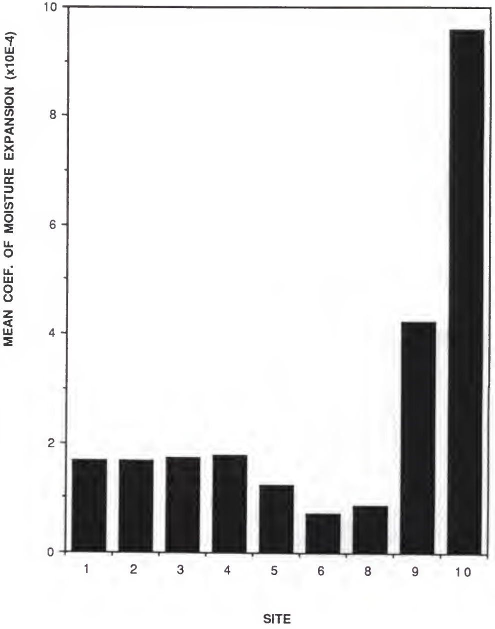

Figure 13.6 Mean Coefficient of Moisture Expansion of In-Service Concrete Pavement

significantly different with the latter being higher than the former.

5. The moisture expansion of the econocrete core samples from the U.S. 41 Econocrete Test Road is significantly higher than that of the concrete samples.

CHAPTER 14
DEVELOPMENT OF PREDICTION EQUATIONS FOR CONCRETE PROPERTIES

14.1 Introduction

This chapter presents the results of linear regression analyses to establish relationships between concrete strength parameters. The analyses were performed using PROC REG procedure of SAS/STAT Release 5.18 software.

The regression coefficient or the coefficient estimate, standard error of the estimate, and the coefficient of variation are given in the tables following the relationships. The standard error of the estimate of the regression parameter in a model measures the amount of variation that exists among the values of that estimate as a result of sampling. Being an indication of the accuracy of the regression coefficient, the standard error of the regression coefficient is used to develop confidence interval on the estimate of the population coefficient. The coefficient of variation, C.V., is computed as the ratio of the square root of the error mean square and the mean of the dependent variable multiplied by 100. It is used for comparison such as the precision of one study with that of another. The smaller the coefficient of variation, the greater the relative accuracy would be.

14.2 Relationship Between the Compressive and Splitting Tensile Strengths

Regression analysis was performed on the 28-day data obtained from the compressive and splitting tensile strength tests using the following models:

$$f_{ct} = a_1\sqrt{f'_c} \tag{14.1}$$

$$f_{ct} = a_2 f'_c \tag{14.2}$$

$$f_{ct} = (f'_c)^{a_3} \tag{14.3}$$

where

f_{ct} = 28-day splitting tensile strength, psi

f'_c = 28-day compressive strength, psi

a_1, a_2, a_3 = coefficients.

The results of the regression analysis are presented in Table 14.1. The prediction equations in the ACI Code [41] showing the relationships between the compressive and splitting tensile strengths for various types of concretes (ACI - 11.2) are as follows:

$$f_{ct} = 6.7\sqrt{f'_c} \text{ for normal weight concrete} \tag{14.4}$$

$$f_{ct} = 5.7\sqrt{f'_c} \text{ for sand-lightweight concrete} \tag{14.5}$$

$$f_{ct} = 5.0\sqrt{f'_c} \text{ for all-lightweight concrete} \tag{14.6}$$

where

f_{ct} = average splitting tensile strength of concrete, psi

Table 14.1 Regression Coefficients for Relation Between Compressive and Splitting Tensile Strengths at 28-Day Moist Curing

Model	Type of Aggregate	Regression Coefficient	Standard Error of the Estimate	Coefficient of Variation
	Brooksville Limestone	5.70724178	0.17603	11.26878
+ $f_t = a_1 \sqrt{f'_c}$	Dense Limestone	5.14037053	0.14780	9.78802
	River Gravel	5.59983153	0.13675	10.17594
(Eq. 14.1)	All 3 Aggregates Combined	5.84478677	0.09309	10.99153
	Brooksville Limestone	0.07497309	0.00328	15.88821
$f_t = a_2 f'_c$	Dense Limestone	0.07356225	0.00191	10.54559
	River Gravel	0.0745307	0.00302	16.74815
(Eq. 14.2)	All 3 Aggregates Combined	0.07420137	0.00150	13.87755
	Brooksville Limestone	0.70269440	0.00422	2.167225
$*f_t = (f'_c)^{a_3}$	Dense Limestone	0.70523286	0.00230	1.305132
	River Gravel	0.70201332	0.00354	2.078505
(Eq. 14.3)	All 3 Aggregates Combined	0.70336219	0.00190	1.833767

* Better relationship.

+ ACI and PCA equation form.

A normal weight concrete is made from natural sand and gravel or crushed-rock aggregates generally weighing about 145 lb/ft^3. "All-lightweight concrete" are those made without natural sand, while lightweight concrete whose fine aggregate is made up of normal weight sand is referred to "sand-lightweight concrete" [41:7]. Lightweight concretes weigh less than about 110 lb/ft^3.

According to PCA [6], the tensile strength of concrete range from about 8 to 12% of the compressive strength. It is estimated as

$$f_{ct} = 5 \text{ to } 7.5 \sqrt{f'_c} \tag{14.7}$$

Ruth [42], and Wang and Salmon [43] consider the splitting tensile strength to be about 8 to 15% and 10 to 15%, respectively, of the compressive strength.

The analysis results presented in Table 14.1 shows that an expression depicted as Equation 14.3 estimates splitting tensile strength better than the ACI expression (Equation 14.1).

Figure 14.1 illustrates the relationship between the compressive and splitting tensile strengths obtained from the laboratory concrete. It is apparent from the figure that the ACI Code formula slightly overestimates the splitting tensile strength of concrete.

14.3 Relationship Between the Compressive Strength and Modulus of Rupture

The following models were used to perform regression analysis relating compressive strength and modulus of rupture:

$$f_r = a_1\sqrt{f'_c} \tag{14.8}$$

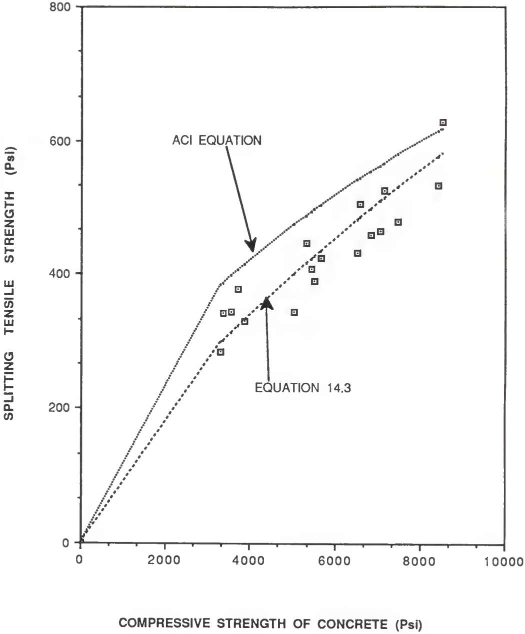

Figure 14.1 Plot of Splitting Tensile Strength Versus Compressive Strength

$$f_r = a_2 f'_c \tag{14.9}$$

$$f_r = (f'_c)^{a_3} \tag{14.10}$$

where

f_r = 28-day modulus of rupture or flexural strength, psi

f'_c = 28-day compressive strength, psi

a_1, a_2, a_3 = coefficients

Table 14.2 contains the results of the regression analysis. Equation 14.10 yields a better relationship.

The modulus of rupture is a measure of the tensile strength in flexure, and is also referred to as the flexural strength.

The following are ACI Code [41] empirical relationships between the compressive strength and modulus of rupture (ACI-9.5.2.3):

$$f_r = 7.5\sqrt{f'_c} \text{ for normal weight concrete} \tag{14.11}$$

$$f_r = 0.75\,(7.5\sqrt{f'_c}) \text{ for all-lightweight concrete} \tag{14.12}$$

$$f_r = 0.85\,(7.5\sqrt{f'_c}) \text{ for sand-lightweight concrete} \tag{14.13}$$

The PCA [6] recommended empirical relationship for a normal weight concrete is

$$f_r = 7.5 \text{ to } 10\sqrt{f'_c} \tag{14.14}$$

According to Fintel [9], the modulus of rupture for both lightweight and normal-weight high-strength concrete (compressive strength greater than 6,000 psi) can be approximated as

$$f_r = 7.5 \text{ to } 12\sqrt{f'_c} \tag{14.15}$$

Table 14.2 Regression Coefficients for Relation Between Compressive Strength and Modulus of Rupture at 28-Day Moist Curing

Model	Type of Aggregate	Regression Coefficient	Standard Error of the Estimate	Coefficient of Variation
+ $f_r = a_1\sqrt{f'_c}$	Brooksville Limestone	9.72379910	0.23591	10.31767
	Dense Limestone	8.99600762	0.17451	7.85771
	River Gravel	10.00779820	0.23281	10.00383
(Eq. 14.8)	All 3 Aggregates Combined	9.55981138	0.13657	10.38890
$f_r = a_2 f'_c$	Brooksville Limestone	0.12541690	0.00616	20.56855
	Dense Limestone	0.10820437	0.00295	11.00386
	River Gravel	0.13192030	0.00458	14.84825
(Eq. 14.9)	All 3 Aggregates Combined	0.12060643	0.00301	17.98504
*$f_r = (f'_c)^{a_3}$	Brooksville Limestone	0.76675537	0.00481	2.66110
	Dense Limestone	0.75009574	0.00235	1.25111
	River Gravel	0.76896836	0.00355	1.96097
(Eq. 14.10)	All 3 Aggregates Combined	0.76221565	0.00244	2.30640

* Better relationship.

+ ACI and PCA equation form.

A constant value of 11.7 was suggested.

Figure 14.2, which presents a plot of modulus of rupture vs. compressive strength, shows that the modulus of rupture calculated using the ACI Code equation is lower at the compressive strength of over 4500 psi. The figure also illustrates that the modulus of rupture increases as the compressive strength increases.

14.4 Relationship Between the Compressive Strength and Static Modulus of Elasticity

The models used to develop linear regression between compressive strength and the static modulus of elasticity are

$$E_c = a_1 w^{1.5} \sqrt{f'_c} \tag{14.16}$$

$$E_c = a_2 w^{1.5} f'_c \tag{14.17}$$

$$E_c = a_3 w f'_c \tag{14.18}$$

where

E_c = 28-day static modulus of elasticity of concrete, psi

w = unit weight of concrete, pcf

f'_c = 28-day compressive strength, psi.

The analysis results are tabulated in Table 14.3.

The average unit weight of concrete batched with Brooksville limestone, dense limestone, and river gravel are 139.83, 145.50, and 142.67 pcf, respectively.

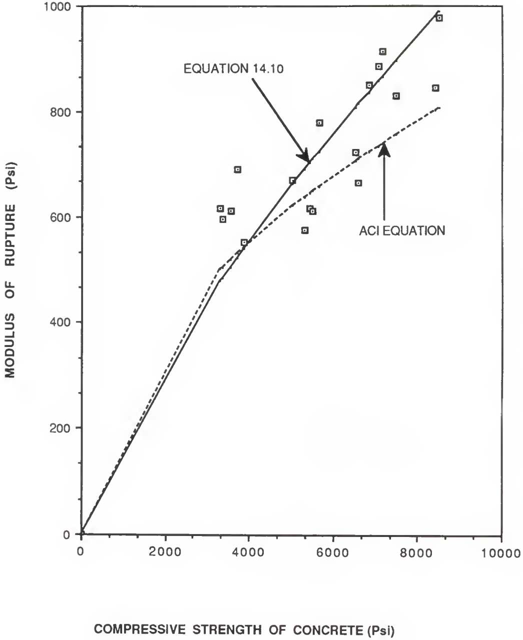

Figure 14.2 Plot of Flexural Strength Versus Compressive Strength

Table 14.3 Regression Coefficients for Relation Between Compression Strength and Static Modulus of Elasticity at 28-Day Moist Curing

Model	Type of Aggregate	Regression Coefficient	Standard Error of the Estimate	Coefficient of Variation
+*$E_c = a_1 w^{1.5} \sqrt{f'_c}$ (Eq. 14.16)	Brooksville Limestone	40.17245618	1.50198	9.20101
	Dense Limestone	44.91056738	1.87867	10.21599
	River Gravel	40.26323847	1.51920	9.24966
	All 3 Aggregates Combined	42.07441370	1.06116	10.76623
$E_c = a_2 w^{1.5} f'_c$ (Eq. 14.17)	Brooksville Limestone	0.52186304	0.04582	21.27832
	Dense Limestone	0.54196429	0.05204	23.02093
	River Gravel	0.53230935	0.05174	23.36541
	All 3 Aggregates Combined	0.53353695	0.02733	21.50924
$E_c = a_3 w f'_c$ (Eq. 14.18)	Brooksville Limestone	6.17942357	0.53435	20.96609
	Dense Limestone	6.53079216	0.63075	23.15594
	River Gravel	6.40081108	0.59958	22.55546
	All 3 Aggregates Combined	6.39209848	0.32481	21.34473

* Better relationship.

+ ACI equation form.

The ACI Code [41] empirical formula relating the compressive strength and the static modulus of elasticity is (ACI-8.5.1)

$$E_c = 33w^{1.5}\sqrt{f'_c} \tag{14.19}$$

for values of w between 90 and 155 lb/ft^3. For normal weight concrete weighing 145 lb/ft^3,

$$E_c = 57{,}000\sqrt{f'_c} \tag{14.20}$$

The regression results presented in Table 14.3 shows that the form of equation used by the ACI Code is a better model. However, regression coefficients of about 40 (Brooksville limestone and river gravel) and 45 (dense limestone) were obtained. The ACI coefficient is 33.

The estimate of the modulus of elasticity using Equations 14.16 and 14.19 are graphed in Figure 14.3.

14.5 Relationship Between the Splitting Tensile Strength and Modulus of Rupture

The relationship between the splitting tensile strength and the modulus of rupture was represented by the following models:

$$f_t = a_1\sqrt{f_r} \tag{14.21}$$

$$f_t = a_2 f_r \tag{14.22}$$

$$f_t = (f_r)^{a_3} \tag{14.23}$$

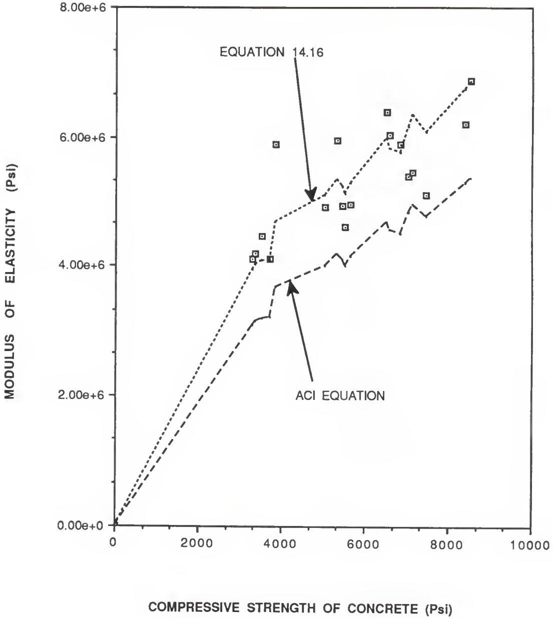

Figure 14.3 Relationship Between Elastic Modulus and Compressive Strength

where

f_t = 28-day splitting tensile strength, psi
f_r = 28-day modulus of rupture, psi
a_1, a_2, a_3 = coefficients.

The linear regression performed using the above models yielded the results contained in Table 14.4.

Although there is no ACI empirical relationship between the splitting tensile strength and modulus of rupture of concrete, a relationship was derived from ACI Code relationships as follows:
Recall that for a normal weight concrete, ACI Code recommends

$$f_{ct} = 6.7 \sqrt{f'_c} \tag{14.4}$$

and

$$f_r = 7.5 \sqrt{f'_c} \tag{14.11}$$

Solving Equation 14.11 for the compressive strength and substituting into Equation 14.4, we have

$$f_{ct} = 0.89 f_r \tag{14.24}$$

An empirical relationship between splitting tensile strength and modulus of rupture derived using PCA Equations 14.7 and 14.14 is

$$f_{ct} = 0.50 \text{ to } 1.0 f_r \tag{14.25}$$

A regression coefficient ranging from about 0.58 to 0.68 was obtained from analysis of test data. A better representation of the

Table 14.4 Regression Coefficients for Relation Between the Splitting Tensile Strength and Modulus of Rupture at 28-Day Moist Curing

Model	Type of Aggregate	Regression Coefficient	Standard Error of the Estimate	Coefficient of Variation
$f_{ct} = a_1 \sqrt{f_r}$ (Eq. 14.21)	Brooksville Limestone	15.48724842	0.62195	14.61503
	Dense Limestone	18.18012488	0.64136	13.81743
	River Gravel	15.12232335	0.41276	11.46022
	All 3 Aggregates Combined	16.24811409	0.37490	15.63516
+ $f_{ct} = a_2 f_r$ (Eq. 14.22)	Brooksville Limestone	0.57874740	0.01506	9.52532
	Dense Limestone	0.67518806	0.01892	11.00856
	River Gravel	0.56241110	0.01322	9.79476
	All 3 Aggregates Combined	0.60492597	0.01172	13.17434
* $f_{ct} = (f_r)^{a_3}$ (Eq. 14.23)	Brooksville Limestone	0.91401647	0.00429	1.69420
	Dense Limestone	0.93934998	0.00475	1.95851
	River Gravel	0.91294310	0.00354	1.59952
	All 3 Aggregates Combined	0.92205203	0.00299	2.17940

* Better relationship.

+ Derived ACI and PCA equation form.

relationship between the splitting tensile strength and modulus of rupture is as expressed in Equation 14.23.

A graphical presentation of the relationship involving splitting tensile strength and modulus of rupture is given in Figure 14.4. The calculated splitting tensile strength using the ACI Code derived expression is higher than that from the best-fit model (Equation 14.23).

14.6 Prediction of Coefficient of Linear Thermal Expansion of Concrete

The factors affecting the coefficient of linear thermal expansion of concrete have already been presented in Section 2.3 of this report. Types of strengths such as compressive and tensile are not known to directly affect thermal expansion. Therefore, the use of an equation relating the coefficient of linear thermal expansion to any of the types of concrete strengths was not considered appropriate.

A range of coefficient of linear thermal expansion of laboratory concrete for water-saturated, oven-dried, and combined water-saturated and oven-dried conditions are presented in Tables 14.5 through 14.7, respectively. The ranges are provided for three categories of concrete based on the compressive strength as follows:

$f'_c < 3000$ psi: low-strength concrete

$f'_c = 3000$ to 5999 psi: medium-strength concrete

$f'_c > 6000$ psi: high-strength concrete

A 95% confidence interval for the mean can be calculated from the expression

$$\text{Mean} \pm t_{0.025} \text{ (Standard error of the Mean)}$$

where

$t_{0.025}$ is obtained from t table.

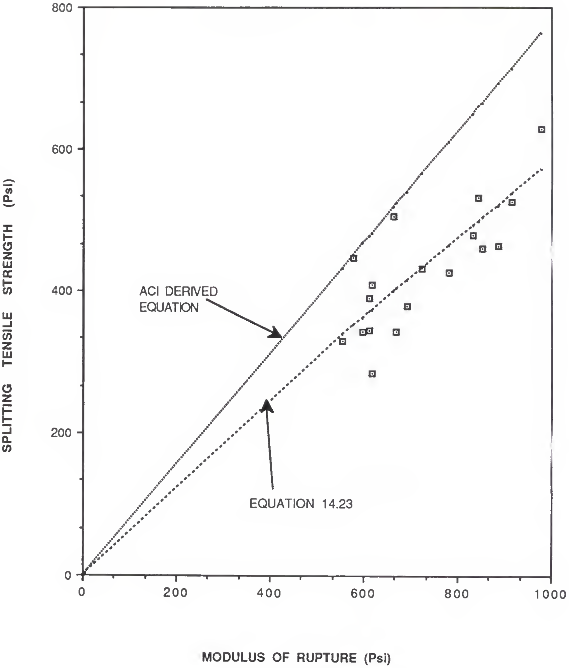

Figure 14.4 Relationship Between Splitting Tensile Strength and Flexural Strength

Table 14.5 Coefficient of Linear Thermal Expansion of Water-Saturated Laboratory Concrete Per Strength Class

Aggregate Type	No. of Observations	Compressive Strength (psi)*	$\times 10^{-6}$ in/in/°F				
			Mean	Minimum Value	Maximum Value	Standard Deviation	Standard Error of Mean
Brooksville	0	< 3000	-	-	-	-	-
	34	3000-5999	5.43	4.65	6.51	0.4137	0.0709
Limestone	32	> 6000	5.40	4.69	5.88	0.2912	0.0514
	66	all classes	5.42	4.65	6.51	0.3572	0.0440
Dense	0	< 3000	-	-	-	-	-
	12	3000-5999	5.86	5.00	6.80	0.4674	0.1349
Limestone	23	> 6000	5.82	5.11	6.37	0.3773	0.0787
	35	all classes	5.83	5.00	6.80	0.4039	0.0683
River	1	< 3000	6.83	6.83	6.83	-	-
	23	3000-5999	6.58	6.04	7.25	0.3567	0.0744
Gravel	11	> 6000	6.27	5.71	7.11	0.4508	0.1359
	35	all classes	6.47	5.71	7.25	0.4084	0.0690

* f'_c < 3000 psi: Low-strength concrete

f'_c = 3000-5999 psi: Medium-strength concrete

f'_c > 6000 psi: High-strength concrete

Table 14.6 Coefficient of Linear Thermal Expansion of Oven-Dried Laboratory Concrete Per Strength Class

Aggregate Type	No. of Observations	Compressive Strength (psi)*	$\times 10^{-6}$ in/in/°F				
			Mean	Minimum Value	Maximum Value	Standard Deviation	Standard Error of Mean
Brooksville Limestone	0	< 3000	-	-	-	-	-
	37	3000-5999	5.66	4.47	6.72	0.5302	0.0872
	31	> 6000	5.71	4.80	6.49	0.4528	0.0813
	68	all classes	5.68	4.47	6.72	0.4934	0.0598
Dense Limestone	0	< 3000	-	-	-	-	-
	13	3000-5999	6.13	5.39	6.67	0.4180	0.1159
	23	> 6000	5.91	4.97	6.41	0.3874	0.0808
	36	all classes	5.99	4.97	6.67	0.4076	0.0679
River Gravel	1	< 300	7.59	7.59	7.59	-	-
	23	3000-5999	7.37	6.62	8.52	0.4619	0.0963
	12	> 6000	6.84	5.65	7.81	0.7705	0.2224
	36	all classes	7.20	5.65	8.52	0.6233	0.1039

* f'_c < 3000 psi: Low-strength concrete

f'_c = 3000-5999 psi: Medium-strength concrete

f'_c > 6000 psi: High-strength concrete

Table 14.7 Combined Water-Saturated and Oven-Dried Coefficient of Linear Thermal Expansion of Laboratory Concrete Specimens Per Strength Class

Aggregate Type	No. of Observations	Compressive Strength (psi)*	$\times 10^{-6}$ in/in/ °F				
			Mean	Minimum Value	Maximum Value	Standard Deviation	Standard Error of Mean
Brooksville Limestone	0	< 3000	-	-	-	-	-
	71	3000-5999	5.55	4.47	6.72	0.4882	0.0579
	63	> 6000	5.55	4.69	6.49	0.4066	0.0512
	134	all classes	5.55	4.47	6.72	0.4500	0.0389
Dense Limestone	0	< 3000	-	-	-	-	-
	25	3000-5999	6.00	5.00	6.80	0.4550	0.0910
	46	> 6000	5.86	4.97	6.41	0.3809	0.0562
	71	all classes	5.91	4.97	6.80	0.4106	0.0487
River Gravel	2	< 3000	7.21	6.83	7.59	0.5374	0.3800
	46	3000-5999	6.97	6.04	8.52	0.5723	0.0844
	23	> 6000	6.57	5.65	7.81	0.6894	0.1438
	71	all classes	6.85	5.65	8.52	0.6360	0.0755

* f'_c < 3000 psi: Low-strength concrete

f'_c = 3000 to 5000 psi: Medium-strength concrete

f'_c > 6000 psi: High-strength concrete

14.7 Prediction of Coefficient of Moisture Expansion

Table 14.8 shows the range of coefficient of moisture expansion values within three categories based on compressive strength per aggregate type. Equations were not developed relating concrete properties such as compressive strength, splitting tensile strength, etc. to coefficient of moisture expansion.

The range of coefficient of moisture expansion for in-service concrete is presented in Table 14.9.

14.8 Summary of Findings

The following empirical relationships considered to better model the respective variables were obtained using 28-day moist-cured data.

1. Compressive versus Tensile Strengths
   - (a) Brooksville Limestone $f_{ct} = (f'_c)^{0.7027}$
   - (b) Dense Limestone $f_{ct} = (f'_c)^{0.7052}$
   - (c) River Gravel $f_{ct} = (f'_c)^{0.7020}$
   - (d) All three aggregates combined $f_{ct} = (f'_c)^{0.7034}$
2. Compressive Strength and Modulus of Rupture
   - (a) Brooksville Limestone $f_r = (f'_c)^{0.7668}$
   - (b) Dense Limestone $f_r = (f'_c)^{0.7501}$
   - (c) River Gravel $f_r = (f'_c)^{0.7690}$
   - (d) All three aggregates combined $f_r = (f'_c)^{0.7622}$
3. Compressive Strength versus Modulus of Elasticity
   - (a) Brooksville Limestone $E_c = 40.1725w^{1.5}\sqrt{f'_c}$
   - (b) Dense Limestone $E_c = 44.9106w^{1.5}\sqrt{f'_c}$
   - (c) River Gravel $E_c = 40.2632w^{1.5}\sqrt{f'_c}$
   - (d) All three aggregates combined $E_c = 42.0744w^{1.5}\sqrt{f'_c}$

Table 14.8 Coefficient of Moisture Expansion of Laboratory Concrete Per Strength Class

Aggregate Type	No. of Observations	Compressive Strength (psi)	x 10^{-4} in/in Mean	Minimum Value	Maximum Value	Standard Deviation	Standard Error of Mean
Brooksville	0	< 3000	-	-	-	-	-
	31	3000-5999	3.38	0.29	7.96	1.2056	0.2165
Limestone	32	> 6000	3.35	2.10	4.63	0.6215	0.1099
	63	all classes	3.36	0.29	7.96	0.9469	0.1193
Dense	0	< 3000	-	-	-	-	-
	7	3000-5999	2.18	1.80	2.57	0.2539	0.0960
Limestone	23	> 6000	2.19	0.79	3.41	0.6990	0.1458
	30	all classes	2.19	0.79	3.41	0.6197	0.1131
River	1	< 3000	3.97	3.97	3.97	-	-
	23	3000-5999	3.49	0.94	8.73	1.5564	0.3245
Gravel	12	> 6000	3.41	2.21	4.97	1.0480	0.3025
	36	all classes	3.48	0.94	8.73	1.3699	0.2283

Table 14.9 Coefficient of Moisture Expansion of In-Service Concrete

Highway (Direction)	Site	No. of Observations	$\times 10^{-4}$ in/in				
			Mean	Minimum Value	Maximum Value	Standard Deviation	Standard Error of Mean
I-75 (Southbound)	1	2	1.67	1.64	1.70	0.0424	0.0300
	2	3	1.68	1.35	2.03	0.3404	0.1966
	3	2	1.72	1.31	2.12	0.5728	0.4050
	4	6	1.77	1.39	2.10	0.2969	0.1212
I-75 (Northbound)	5	3	1.25	1.07	1.36	0.1550	0.0895
	6	3	0.72	0.57	0.90	0.1662	0.0960
U.S. 41 Econocrete Test Road (Southbound)	7	3	0.86	0.75	1.08	0.1905	0.1100
	8	2	4.22	3.53	4.90	0.9687	0.6850
	9	1	9.59	9.59	9.59	-	-

where the unit weights and standard deviations for Brooksville limestone, dense limestone, and river gravel are 139.83 pcf and 2.69, 142.67 pcf and 3.01, and 145.50 pcf and 1.64, respectively.

4. Splitting Tensile Strength and Modulus of Rupture

   (a) Brooksville Limestone $f_{ct} = (f_r)^{0.9140}$

   (b) Dense Limestone $f_{ct} = (f_r)^{0.9393}$

   (c) River Gravel $f_{ct} = (f_r)^{0.9129}$

   (d) All three aggregates combined $f_{ct} = (f_r)^{0.9221}$

CHAPTER 15
OPTIMIZATION OF CONCRETE MIX DESIGN FOR CONCRETE PAVEMENT

15.1 Introduction

The effect of temperature differential across the thickness of a pavement slab has been studied by some researchers. Armaghani, Larsen, and Smith [44], and Yoder and Witzack [45] observed that pavement slab curled upward at the edges when the bottom temperature was greater than that at the surface (negative temperature differential). On the other hand, upward curling at the pavement center and downward curling along the edges was caused by positive temperature differential, a condition when the surface temperature exceeds that of the bottom (see Figure 15.1).

Analysis of structural response of concrete pavement under critical thermal loading conditions was performed by Tia et al. [46]. One of the effects on the maximum load-induced stresses analyzed was that of elastic modulus of concrete. In the said study, a typical pavement system with the following parameters was used in the analysis:

1. Slab thickness = 9 inches
2. Slab length = 20 ft
3. Subgrade modulus, K_s = 500 pci
4. Edge stiffness, K_e = 500 Ksi
5. Jont linear stiffness, K_l = 250 Ksi
6. Joint torsional stiffness, K_t = 1000 K-in/in (4.45 MN-m/m)

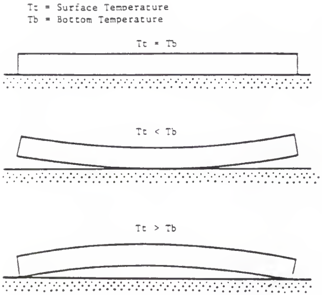

Figure 15.1 Curling of Concrete Pavement Due to Temperature Differential [44]

7. External load = 22 Kips (98 KN). Single-axle applied at the center of the slab
8. Temperature differential, ΔT = +20°F (+11.1°C)

Figure 15.2 shows the relationship of maximum stresses obtained at various elastic moduli of concrete. The maximum longitudinal and transverse stresses were found to be directly proportional to the elastic modulus of concrete. It was concluded that (1) an increase in elastic modulus of concrete pavement without a corresponding increase in flexural strength of concrete will cause deplorable conditions, and (2) a concrete pavement possessing high elastic modulus may be of disservice because of lack of corresponding increase in flexural strength.

In order to optimize a concrete mix for pavement application, the effects of coefficient of thermal expansion and elastic modulus of concrete on thermal load-induced stresses must be comprehended.

15.2 Effects of Thermal Expansion and Modulus of Elasticity of Concrete

The effects of the thermal expansion and modulus of elasticity of concrete on the thermal load-induced stresses in the concrete slab were evaluated using the FEACONS IV program. FEACONS IV is an acronym for version four of the Finite Element Analysis of CONcrete Slabs computer program developed at the University of Florida.

A typical concrete pavement system with the following dimensions and parameters was used:

1. Slab thickness = 10 inches
2. Slab length = 20 ft
3. Subgrade modulus, K_s = 0.300 Kci
4. Edge stiffness, K_e = 7.50 Ksi

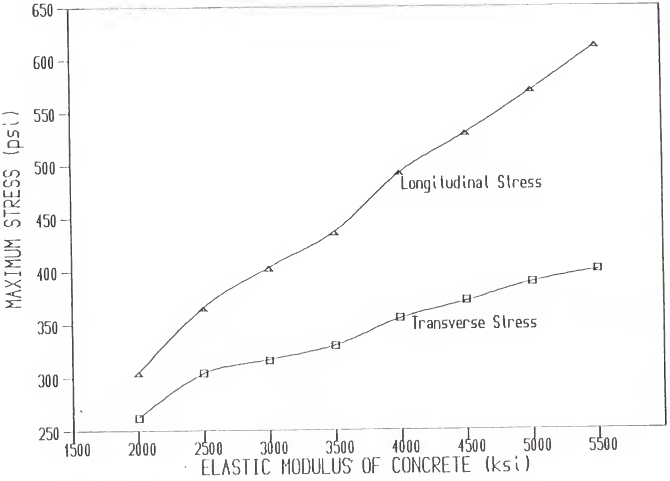

Figure 15.2 Effect of Concrete Modulus on Maximum Stresses Caused by a 22-Kip Axle Load and a Temperature Differential of +20°F [46]

5. Joint linear stiffness, K_l = 30 Ksi
6. Joint torsional stiffness, K_t = 250 K-in/in

The maximum longitudinal stresses in the concrete slab caused by the combination of a 22-Kip single-axle load applied at the edge of the slab and a temperature differential of +20°F in the slab were computed at various moduli of elasticity and coefficient of thermal expansion of concrete (see Table 15.1). The computed maximum longitudinal stresses are plotted in Figure 15.3. It shows that as the modulus of elasticity and coefficient of thermal expansion increases, so does the maximum longitudinal stress. Therefore, increasing the modulus of elasticity of concrete without a corresponding increase in the flexural strength of the concrete at a given coefficient of thermal expansion could lead to poor pavement performance. The degree of poor pavement performance may increase as the coefficient of thermal expansion increases. The plot of the combination of modulus of elasticity and the coefficient of thermal expansion of concrete to produce various maximum stress is presented in Figure 15.4. The figure shows that to maintain a constant maximum stress, the modulus of elasticity has to be decreased as the coefficient of expansion increases.

15.3 Optimizing Concrete Pavement Mix Design

It has been pointed out in the previous sections that stress in the concrete increases as the modulus of elasticity increases for a given coefficient of thermal expansion. To maintain a constant given maximum stress, the modulus of elasticity of concrete must decrease as the coefficient of thermal expansion increases. For a concrete pavement to provide satisfactory performance through the entire design life, the

Table 15.1 Computed Maximum Longitudinal Stress Using FEACONS IV Program

Coefficient of Thermal Expansion	Modulus of Elasticity of Concrete, E_c (Ksi)												
	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000
5.0×10^{-6}/°F	393.7	430.8	465.2	501.9	535.0	562.8	593.7	618.0	647.1	673.6	700.8	724.5	747.5
5.5×10^{-6}/°F	412.3	450.0	491.8	529.9	559.7	599.6	624.2	655.1	685.3	712.6	739.3	765.1	790.0
6.0×10^{-6}/°F	428.4	473.4	514.6	549.6	591.6	622.1	657.7	688.9	719.2	748.6	777.0	804.5	826.1
6.5×10^{-6}/°F	445.0	495.5	533.9	579.7	614.5	652.6	687.0	721.3	753.3	785.1	809.9	844.3	867.4

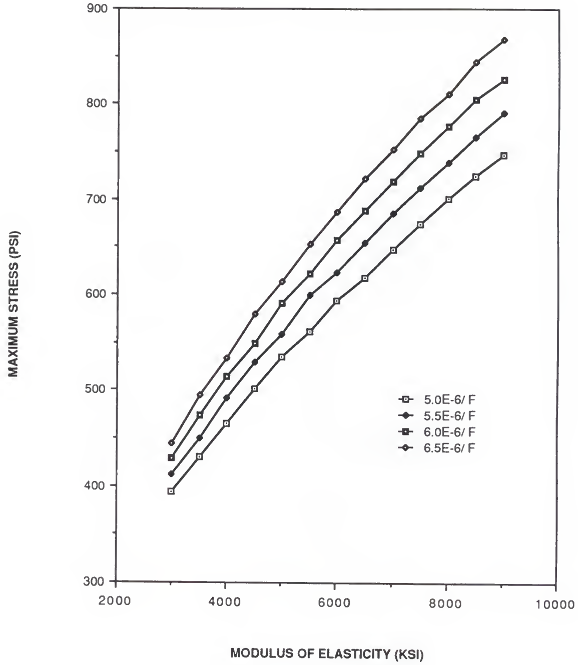

Figure 15.3 Computed Maximum Longitudinal Stress Using FEACONS IV Program

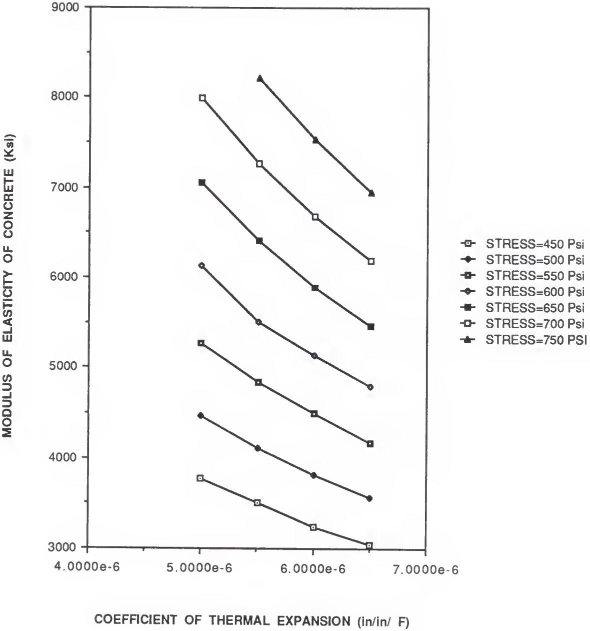

Figure 15.4 Combinations of Modulus of Elasticity and Coefficient of Thermal Expansion of Concrete to Produce Fixed Maximum Stresses

maximum thermal load-induced stress in the slab must be kept low. But reducing the stress in the concrete entails the use of concrete with low modulus of elasticity.

The flexural strength or the modulus of rupture is the maximum stress at rupture. Since concrete pavements are loaded in bending, it will be appropriate to use concretes with modulus of rupture higher than the thermal load stresses. The ratio of maximum thermal load-induced stress divided by the modulus of rupture of concrete is referred to as stress ratio. That is,

$$\text{Stress Ratio} = \frac{\text{Maximum Thermal Load Stress}}{\text{Modulus of Rupture}}$$

Apparently an optimal concrete mix is one with minimum stress ratio and has a reasonable material and construction cost. Table 15.2 summarizes the results of computed maximum thermal load-induced stresses and stress ratios using the mean 28-day values of the modulus of rupture, modulus of elasticity, and water-saturated coefficient of thermal expansion of laboratory concrete. The maximum thermal load-induced stresses were caused by a 22-kip single axle load applied to the edge of a 10-inch thick pavement slab with a temperature differential of +20°F. It can be noted from Table 15.2 that the computed maximum stress increases as the W/C ratio decreases. However, since the flexural strength increases as the W/C ratio decreases, the stress ratio decreases as the W/C ratio decreases. The effect of W/C ratio on stress ratio is greater for the concretes made with river gravel and dense limestone than that for the concrete made with Brooksville limestone. At the higher W/C ratios (0.53 or 0.45), the concrete made with Brooksville limestone has a lower

Table 15.2 Computed Maximum Load-Induced Stresses and Stress Ratios Using Mean 28-Day Values of Modulus of Rupture, Modulus of Elasticity, and Water-Saturated Coefficient of Thermal Expansion of Laboratory Concrete

Aggregate Type	W/C	Cement Content (lb/cy)	Mean 28-Day Water-Saturated Coef. of Thermal Expansion (x 10E-6/°F)	Mean 28-Day Modulus of Elasticity (Ksi)	Mean 28-Day Modulus of Rupture (psi)	Computed Stress (psi)	Stress Ratio
Brooksville Limestone	0.53	508	5.34	4120	653.33	492.70	0.75
		564	5.67	3815	620.00	485.17	0.78
	0.45	564	5.41	4780	674.67	540.21	0.80
		658	5.34	4325	702.67	506.48	0.72
	0.38	658	5.29	5345	746.17	570.47	0.76
	0.33	752	5.65	4995	811.67	567.95	0.70
River Gravel	0.53	508	6.87	4325	604.17	579.26	0.96
	0.45	564	6.38	4925	643.17	602.16	0.94
	0.33	752	6.47	5425	899.17	645.69	0.72
Dense Limestone	0.53	508	6.12	5930	565.17	660.11	1.17
	0.45	564	5.87	6210	694.00	663.03	0.96
	0.33	752	5.63	6535	910.83	667.52	0.73

stress ratio than those made with dense limestone or river gravel. At the low W/C ratio (0.33), all the three aggregate types gave approximately the same stress ratio. For the concrete made with Brooksville limestone, since the stress ratio does not vary greatly (it ranges from 0.70 to 0.80) as the W/C is reduced, it appears that the use of a higher W/C (such as 0.53) would be more cost effective. At a W/C of 0.53, which is normally used on pavement concrete, the Brooksville aggregate should give better performance than the dense limestone or the river gravel, based on the computed stress ratio.

CHAPTER 16
CONCLUSIONS AND RECOMMENDATIONS

16.1 Introduction

An extensive study of the laboratory-batched and in-service concrete specimens was executed principally to determine the coefficient of linear thermal and moisture of concrete used in Florida at temperatures ranging from 77 to 140°F (25 to 60°C). Under study were three types of aggregate, four levels of water-cement ratio, four levels of cement content, and two levels of moist-curing duration. The effects of the above factors on the strength parameters were also analyzed. The conclusions and recommendations arrived at from the study are presented in this chapter.

16.2 Conclusions

The summary of the major findings from the study are

1. Aggregate types have some effects on the strength properties of concrete. At W/C ratios of 0.33 and 0.45, the compressive strengths of concretes made with Brooksville limestone and river gravel are not significantly different from each other but are significantly lower than those made with the dense limestone. At a W/C of 0.53, the three aggregates produced about the same compressive strength. The splitting tensile strength and modulus of rupture of concretes made with Brooksville limestone and river gravel are not significantly different from each other but

are significantly lower than those of concrete made with the dense limestone. Concrete made with dense limestone had the highest modulus of elasticity, followed by river gravel and lastly Brooksville limestone.

2. The concrete made with river gravel had the highest coefficient of thermal expansion, followed by concrete made with dense limestone, while concrete made with Brooksville limestone had the lowest coefficient of thermal expansion.
3. The concrete made with dense limestone had the lowest coefficient of moisture expansion, while the concrete made with Brooksville limestone had the highest coefficient of moisture expansion.
4. The compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity of concrete generally increase as the water-cement ratio decreases. The water-cement ratio has no noticeable effect on the coefficient of moisture expansion, and coefficient of linear thermal expansion.
5. The properties of hardened concrete are significantly affected by the moist-curing duration. The longer the concrete is moist-cured, the higher the compressive strength, modulus of rupture, and modulus of elasticity would be. The lower moist-curing duration produces lower coefficient of linear thermal expansion of concrete at oven-dried condition and lower coefficient of moisture expansion. The coefficient of linear thermal expansion of concrete at water-saturated condition was not significantly affected by moist-curing duration.

6. The coefficient of linear thermal expansion of water-saturated and oven-dried laboratory concrete were significantly different from each other. The coefficient is relatively lower at water-saturated condition.
7. The compressive strengths of the concrete samples obtained in this study from existing concrete pavements in Florida exceeded the FDOT compressive strength requirement for class I concrete.
8. The splitting tensile strengths of the econocrete samples obtained from U.S. 41 Econocrete Test Road are generally about half of those of the concrete samples from the other pavements. The splitting tensile strengths of in-service concrete samples are about 8% of their compressive strengths.
9. The coefficient of linear thermal expansion of oven-dried in-service concrete is significantly different from that of water-saturated in-service concrete with the former being lower than the latter.
10. The coefficient of moisture expansion of the econocrete core samples obtained from the U.S. 41 Econocrete Test Road is significantly higher than that of the concrete samples.
11. Empirical relationships of the form $f_{ct} = (f'_c)^{a_1}$, $f_r = (f'_c)^{a_2}$, and $f_{ct} = (f_r)^{a_3}$ where a_1, a_2, and a_3 are regression coefficients were found to fit the test data better than the expressions of the form $f_{ct} = a_1 \sqrt{f'_c}$, $f_r = a_2\sqrt{f'_c}$, and $f_{ct} = a_3 f_r$, respectively.

12. The following empirical relationships between the various concrete properties represented the best fits to the results of tests on the 28-day moist-cured concrete.

    A. Compressive versus Tensile Strengths

    1) Brooksville Limestone $f_{ct} = (f'_c)^{0.7027}$
    2) Dense Limestone $f_{ct} = (f'_c)^{0.7052}$
    3) River Gravel $f_{ct} = (f'_c)^{0.7020}$
    4) All three aggregates combined $f_{ct} = (f'_c)^{0.7034}$

    B. Compressive Strength and Modulus of Rupture

    1) Brooksville Limestone $f_r = (f'_c)^{0.7668}$
    2) Dense Limestone $f_r = (f'_c)^{0.7501}$
    3) River Gravel $f_r = (f'_c)^{0.7690}$
    4) All three aggregates combined $f_r = (f'_c)^{0.7622}$

    C. Compressive Strength Versus Modulus of Elasticity

    1) Brooksville Limestone $E_c = 40.1725w^{1.5} \sqrt{f'_c}$
    2) Dense Limestone $E_c = 44.9106w^{1.5} \sqrt{f'_c}$
    3) River Gravel $E_c = 40.2632w^{1.5} \sqrt{f'_c}$
    4) All three aggregates combined $E_c = 42.0744w^{1.5} \sqrt{f'_c}$

    The average unit weight of concrete batched with Brooksville limestone, dense limestone, and river gravel are 139.83 pcf, 142.67 pcf, and 145.50 pcf, respectively.

13. The ranges of coefficient of linear thermal expansion and coefficient of moisture expansion of the concrete studied are presented in Tables 16.1 through 16.5.

Table 16.1 Range of Coefficient of Linear Thermal Expansion of Water-Saturated Laboratory Concrete

Aggregate Type	Compressive Strength (Psi)	Range x 10^{-6} in/in/°F
Brooksville	3000-5999	4.65 - 6.51
	> 6000	4.69 - 5.88
Limestone	All classes	4.65 - 6.51
Dense	3000-5999	5.00 - 6.80
	> 6000	5.11 - 6.37
Limestone	All classes	5.00 - 6.80
River	< 3000	6.83
	3000-5999	6.04 - 7.25
Gravel	> 6000	5.71 - 7.11
	All classes	5.71 - 7.25

Table 16.2 Range of Coefficient of Linear Thermal Expansion of Oven-Dried Laboratory Concrete

Aggregate Type	Compressive Strength (Psi)	Range x 10^{-6} in/in/°F
Brooksville	3000-5999	4.47 - 6.72
	> 6000	4.80 - 6.49
Limestone	All classes	4.47 - 6.72
Dense	3000-5999	5.39 - 6.67
	> 6000	4.97 - 6.41
Limestone	All classes	4.97 - 6.67
River	< 3000	7.59
	3000-5999	6.62 - 8.52
Gravel	> 6000	5.65 - 7.81
	All classes	5.65 - 8.52

Table 16.3 Range of Coefficient of Linear Thermal Expansion of Laboratory Concrete at Water-Saturated and Oven-Dried Conditions

Aggregate Type	Compressive Strength (Psi)	Range x 10^{-6} in/in/°F
Brooksville Limestone	3000-5999	4.47 - 6.72
	> 6000	4.69 - 6.49
	All classes	4.47 - 6.72
Dense Limestone	3000-5999	5.00 - 6.80
	> 6000	4.97 - 6.41
	All classes	4.97 - 6.80
River Gravel	< 3000	6.83 - 7.59
	3000-5999	6.04 - 8.52
	> 6000	5.65 - 7.81
	All classes	5.65 - 8.52

Table 16.4 Range of Coefficient of Moisture Expansion of Laboratory Concrete

Aggregate Type	Compressive Strength (Psi)	Range x 10^{-4}in/in
Brooksville Limestone	3000-5999	0.29 - 7.96
	> 6000	2.10 - 4.63
	All classes	0.29 - 7.96
Dense Limestone	3000-5999	1.80 - 2.57
	> 6000	0.79 - 3.41
	All classes	0.79 - 3.41
River Gravel	< 3000	3.97
	3000-5999	0.94 - 8.73
	> 6000	2.21 - 4.97
	All classes	0.94 - 8.73

Table 16.5 Range of Coefficient of Moisture Expansion of In-Service Concrete

Highway (Direction)	Site	Range x 10^{-4} in/in
I-75 (Southbound)	1	1.64 - 1.70
	2	1.35 - 2.03
	3	1.31 - 2.12
	4	1.39 - 2.10
I -75 (Northbound)	5	1.07 - 1.36
	6	0.57 - 0.90
U.S. 41 Econocrete Test Road (Southbound)	7	0.75 - 1.08
	8	3.53 - 4.90
	9	9.59

16.3 Recommendations

Based on the findings from this study, the following recommendations are made:

1. In the evaluation of potential performance of a pavement concrete in service, the ratio between the maximum anticipated stress in the concrete and the flexural strength of the concrete should be considered. The lower this stress ratio is, the better should be the performance of the concrete in service. The maximum stress in the concrete is a function of the coefficient of thermal expansion, coefficient of moisture expansion and elastic modulus of the concrete.
2. For pavement concrete with a W/C of around 0.5, the use of Brooksville limestone should give better performance than the dense limestone or river gravel.
3. When Brooksville limestone is used in pavement concrete, the change in W/C of the concrete mix should not affect its structural performance significantly. Thus, the use of a W/C of around 0.5 should be appropriate since it is more cost effective, as compared with one of lower W/C.

16.4 Recommendations for Further Research

The following are reommended for further research:

1. The coefficient of thermal expansion of the aggregates used in Florida and the cement paste should be determined, and related to that of the concrete.
2. The coefficient of thermal expansion of concretes containing silica fume, slag, and pozzolan cement should be investigated.

3. The effects of different sizes of aggregate and different proportioning of aggregate to cement paste ratio on the coefficient of thermal expansion should be studied.
4. More refined instrumentation needs to be developed for the study of thermal and hygroscopic properties of concrete to reduce the scattering of measured data.

APPENDIX A

MIX PROPORTIONS OF CONCRETE MIXES

Appendix A Mix Proportions of Concrete Mixes

Aggregate Type (max. size=3/8")	W/C	Cement Content (lb/cy)	Cement Type	Replicate	Water (lb/cy)	Sand (lb/cy)	Coarse Agg. (lb/cy)	Admixtures RD-1 (ml/cy)	Admixtures DAREX (ml/cy)
Brooksville Limestone	0.53	508	II	1	288	1593	1277	293	124
			II	2	311	1558	1274	0	126
		564	II	1	300	1486	1275	0	126
			II	2	331	1443	1229	0	88
	0.45	564	II	1	292	1570	1274	412	102
			II	2	296	1552	1274	1280	116
		658	II	1	316	1396	1274	149	99
			II	2	325	1363	1237	0	96
	0.38	658	II	1	279	1496	1274	1250	124
			II	2	277	1498	1274	1340	124
	0.33	752	II	1	280	1419	1229	1080	88
			II	2	298	1415	1215	540	92

Appendix A Continued.

Aggregate		Cement					Coarse	Admixtures	
Type (max. size=3/8")	W/C	Content (lb/cy)	Cement Type	Replicate	Water (lb/cy)	Sand (lb/cy)	Agg. (lb/cy)	RD-1 (ml/cy)	DAREX (ml/cy)
River Gravel	0.53	508	II	1	283	1530	1397	360	72
			II	2	285	1527	1398	0	72
	0.45	564	II	1	270	1520	1398	780	80
			II	2	271	1520	1397	660	80
	0.33	752	II	1	263	1379	1398	1020	80
			II	2	264	1379	1398	1560	80
Dense Limestone	0.53	508	II	1	273	1637	1340	2160	72
			II	2	234	1757	1123	2070	72
	0.45	564	II	1	219	1752	1123	2220	80
			II	2	219	1752	1123	2560	80
	0.33	752	II	1	232	1599	1122	1960	80
			II	2	213	1620	1123	1960	80

APPENDIX B

PROPERTIES OF FRESH CONCRETE

Appendix B Properties of Fresh Concrete

Aggregate Type (max. size=3/8")	W/C	Cement Content (lb/cy)	Replicate	Slump (in)	Air Content (%)	Unit Weight (lb/cf)
Brooksville Limestone	0.53	508	1	1.0	5.5	139
			2	1.25	6.0	137
		564	1	2.0	5.75	137
			2	2.5	6.0	136
	0.45	564	1	0.6	5.5	139
			2	2.25	6.0	141
		658	1	2.5	3.0	142
			2	2.5	6.0	138
	0.38	658	1	2.0	5.6	143
			2	1.5	6.0	145
	0.33	752	1	2.5	5.0	141
			2	2.0	6.0	140

Appendix B Continued.

Aggregate Type (max. size=3/8")	W/C	Cement Content (lb/cy)	Replicate	Slump (in)	Air Content (%)	Unit Weight (lb/cf)
River Gravel	0.53	508	1	2.5	6.0	140
			2	2.5	6.0	139
	0.45	564	1	2.0	6.0	143
			2	1.75	6.0	142
	0.33	752	1	2.0	4.75	147
			2	2.75	6.0	145
Dense Limestone	0.53	508	1	1.75	5.0	148
			2	0.6	5.0	145
	0.45	564	1	1.25	5.5	143
			2	0.5	5.0	146
	0.33	752	1	2.5	4.75	145
			2	0.5	5.0	146

APPENDIX C

LENGTH READINGS OF WATER-SATURATED LABORATORY CONCRETE SPECIMENS

COEFFICIENT OF THERMAL EXPANSION
WATER-SATURATED SPECIMENS
LABORATORY STUDY

LEGEND

COLUMN A = BATCH NUMBER
COLUMN B = WATER-CEMENT RATIO
COLUMN C = TYPE OF AGGREGATE
COLUMN D = MOIST-CURING DURATION (DAYS)
COLUMN E = CEMENT CONTENT (lb/cy)
COLUMN F = SPECIMEN IDENTIFICATION NUMBERS (SEPARATED BY DASHES)
COLUMN G = SPECIMEN TEMPERATURE
COLUMN H = LENGTH OF FIRST SPECIMEN IN COL. F
COLUMN I = LENGTH OF SECOND SPECIMEN IN COL. F
COLUMN J = LENGTH OF THIRD SPECIMEN IN COL. F

A	B	C	D	E	F	G	H	I	J
1	0.53	BL	28	564	3-6	82.4	11.854171	11.845114	
1	0.53	BL	28	564	3-6	106.7	11.855471	11.846541	
1	0.53	BL	28	564	3-6	120.2	11.856296	11.847500	
1	0.53	BL	28	564	3-6	140.0	11.857448	11.848761	
1	0.53	BL	28	564	4	74.0	11.809544		
1	0.53	BL	28	564	4	99.0	11.811343		
1	0.53	BL	28	564	4	123.0	11.823144		
1	0.53	BL	28	564	4	140.0	11.824718		
1	0.53	BL	90	564	1-5-7	74.0	11.825045	11.814928	11.785708
1	0.53	BL	90	564	1-5-7	103.0	11.826834	11.815931	11.788249
1	0.53	BL	90	564	1-5-7	121.0	11.827999	11.817325	11.790143
1	0.53	BL	90	564	1-5-7	140.0	11.829358	11.818838	11.792236
2	0.53	BL	28	508	2-1-6	79.7	11.869510	11.849036	11.872160
2	0.53	BL	28	508	2-1-6	104.0	11.870450	11.850851	11.873799
2	0.53	BL	28	508	2-1-6	122.0	11.871360	11.852068	11.875194
2	0.53	BL	28	508	2-1-6	139.0	11.872276	11.853020	11.875891
2	0.53	BL	90	508	3-7-9	74.5	11.708033	11.725608	11.683303
2	0.53	BL	90	508	3-7-9	103.0	11.709987	11.727568	11.685328
2	0.53	BL	90	508	3-7-9	124.0	11.711126	11.729106	11.68716[illegible]
2	0.53	BL	90	508	3-7-9	142.0	11.712424	11.730478	11.688358
3	0.45	BL	28	658	1-2-7	73.0	11.847036	11.797565	11.878315
3	0.45	BL	28	658	1-2-7	103.0	11.848479	11.799173	11.879088
3	0.45	BL	28	658	1-2-7	122.0	11.849879	11.800195	11.880246
3	0.45	BL	28	658	1-2-7	142.0	11.850998	11.801613	11.881434
3	0.45	BL	90	658	3-5-8	74.0	11.792458	11.792125	11.844740
3	0.45	BL	90	658	3-5-8	102.0	11.794186	11.793949	11.846434
3	0.45	BL	90	658	3-5-8	121.0	11.795193	11.795150	11.847653
3	0.45	BL	90	658	3-5-8	141.0	11.796383	11.796415	11.849125

4	0.45	BL	28	564	2-4-8	74.0	11.805200	11.783778	11.727326
4	0.45	BL	28	564	2-4-8	103.0	11.806964	11.785176	11.729056
4	0.45	BL	28	564	2-4-8	121.0	11.808144	11.786486	11.730315
4	0.45	BL	28	564	2-4-8	140.0	11.809584	11.787931	11.731616
4	0.45	BL	90	564	5-6-7	76.0	11.772154	11.689433	11.722700
4	0.45	BL	90	564	5-6-7	104.0	11.774056	11.691281	11.724639
4	0.45	BL	90	564	5-6-7	122.0	11.775006	11.692083	11.725558
4	0.45	BL	90	564	5-6-7	142.0	11.776425	11.693534	11.726809
5	0.38	BL	28	658	3-5-7	74.5	11.841665	11.835581	11.838748
5	0.38	BL	28	658	3-5-7	103.0	11.843486	11.837320	11.840370
5	0.38	BL	28	658	3-5-7	124.0	11.844944	11.838656	11.841456
5	0.38	BL	28	658	3-5-7	142.0	11.846104	11.839889	11.842524
5	0.38	BL	28	658	1-4-8	77.0	11.824335	11.811698	11.83546
5	0.38	BL	28	658	1-4-8	100.0	11.825771	11.813128	11.836836
5	0.38	BL	28	658	1-4-8	122.0	11.827036	11.814543	11.838084
5	0.38	BL	28	658	1-4-8	142.0	11.828461	11.815885	11.839616
6	0.38	BL	28	658	1-3-8	74.0	11.826215	11.882474	11.875175
6	0.38	BL	28	658	1-3-8	105.0	11.828338	11.884706	11.877355
6	0.38	BL	28	658	1-3-8	122.0	11.829398	11.885818	11.878524
6	0.38	BL	28	658	1-3-8	139.0	11.830359	11.886829	11.878895
6	0.38	BL	28	658	4-5-8	74.0	11.874553	11.874553	11.818467
6	0.38	BL	28	658	4-5-8	101.0	11.835559	11.875991	11.819956
6	0.38	BL	28	658	4-5-8	122.0	11.836945	11.877295	11.821308
6	0.38	BL	28	658	4-5-8	141.0	11.838318	11.878659	11.822604
7	0.45	BL	90	564	1-4-5	76.0	11.864688	11.834983	11.817421
7	0.45	BL	90	564	1-4-5	104.0	11.866453	11.836004	11.819440
7	0.45	BL	90	564	1-4-5	121.0	11.867475	11.837063	11.820396
7	0.45	BL	90	564	1-4-5	140.0	11.868758	11.838169	11.821383
7	0.45	BL	90	564	3-6-8	75.0	11.788650	11.841030	11.838039
7	0.45	BL	90	564	3-6-8	104.0	11.790214	11.842768	11.839731
7	0.45	BL	90	564	3-6-8	128.0	11.791733	11.844393	11.841144
7	0.45	BL	90	564	3-6-8	142.0	11.792225	11.845339	11.841901
8	0.53	BL	28	508	1-4-5	76.0	11.806005	11.887953	11.837278
8	0.53	BL	28	508	1-4-5	104.0	11.807460	11.889738	11.83915
8	0.53	BL	28	508	1-4-5	121.0	11.808025	11.890875	11.840118
8	0.53	BL	28	508	1-4-5	140.0	11.809068	11.891815	11.841063
8	0.53	BL	28	508	2-3-6	70.0	11.857959	11.846756	11.776119
8	0.53	BL	28	508	2-3-6	107.0	11.860008	11.849044	11.778391
8	0.53	BL	28	508	2-3-6	122.0	11.860971	11.849993	11.779380
8	0.53	BL	28	508	2-3-6	143.0	11.862336	11.851419	11.780726
9	0.45	BL	90	658	1-2-6	71.0	11.867524	11.822100	11.813285
9	0.45	BL	90	658	1-2-6	103.0	11.869430	11.824014	11.815358
9	0.45	BL	90	658	1-2-6	126.0	11.870888	11.825495	11.816685
9	0.45	BL	90	658	1-2-6	139.0	11.871960	11.826533	11.817814

9	0.45	BL	90	658	3-7-8	73.0	11.792576	11.759663	11.791845
9	0.45	BL	90	658	3-7-8	100.0	11.794225	11.761199	11.793499
9	0.45	BL	90	658	3-7-8	123.0	11.795704	11.762713	11.795046
9	0.45	BL	90	658	3-7-8	140.0	11.797034	11.764069	11.796223
10	0.33	BL	90	752	2-5-7	74.0	11.771350	11.798994	11.746950
10	0.33	BL	90	752	2-5-7	102.0	11.773281	11.800839	11.748671
10	0.33	BL	90	752	2-5-7	121.0	11.775561	11.802006	11.749665
10	0.33	BL	90	752	2-5-7	141.0	11.775989	11.803440	11.751034
10	0.33	BL	90	752	1-3-6	74.0	11.789759	11.774034	11.781155
10	0.33	BL	90	752	1-3-6	96.0	11.791086	11.775565	11.782601
10	0.33	BL	90	752	1-3-6	123.0	11.792459	11.777168	11.784114
10	0.33	BL	90	752	1-3-6	140.0	11.793780	11.778531	11.785581
11	0.53	BL	28	564	4-6-7	76.0	11.781526	11.722196	11.736958
11	0.53	BL	28	564	4-6-7	100.0	11.783261	11.724123	11.738959
11	0.53	BL	28	564	4-6-7	122.0	11.784661	11.725584	11.740435
11	0.53	BL	28	564	4-6-7	140.0	11.785796	11.726995	11.741633
11	0.53	BL	28	564	1-3-8	74.0	11.733791	11.729230	11.759335
11	0.53	BL	28	564	1-3-8	99.0	11.735336	11.730794	11.760896
11	0.53	BL	28	564	1-3-8	123.0	11.736769	11.732289	11.762208
11	0.53	BL	28	564	1-3-8	140.0	11.738139	11.733423	11.763489
12	0.33	BL	90	752	4-7-8	76.0	11.767341	11.759000	11.726228
12	0.33	BL	90	752	4-7-8	100.0	11.769123	11.760730	11.727988
12	0.33	BL	90	752	4-7-8	122.0	11.770475	11.762099	11.729358
12	0.33	BL	90	752	4-7-8	140.0	11.771703	11.763358	11.730620
12	0.33	BL	90	752	1-5-6	76.0	11.769775	11.745964	11.748318
12	0.33	BL	90	752	1-5-6	107.0	11.771691	11.747960	11.750391
12	0.33	BL	90	752	1-5-6	123.0	11.772441	11.749001	11.751155
12	0.33	BL	90	752	1-5-6	140.0	11.773583	11.750146	11.752433
13	0.53	RG	90	508	1-3-5	83.0	11.695463	11.742469	11.740061
13	0.53	RG	90	508	1-3-5	122.0	11.698406	11.745416	11.742780
13	0.53	RG	90	508	1-3-5	140.0	11.700066	11.746801	11.744418
13	0.53	RG	90	508	2-4-6	76.0	11.720879	11.685966	11.712629
13	0.53	RG	90	508	2-4-6	107.0	11.723445	11.688614	11.71522
13	0.53	RG	90	508	2-4-6	123.0	11.724623	11.689711	11.71627
13	0.53	RG	90	508	2-4-6	140.0	11.726140	11.691159	11.717768
14	0.33	RG	28	752	4-6-8	72.0	11.632023	11.731594	11.689308
14	0.33	RG	28	752	4-6-8	106.0	11.634100	11.733536	11.691340
14	0.33	RG	28	752	4-6-8	120.0	11.635625	11.735065	11.692688
14	0.33	RG	28	752	4-6-8	140.0	11.637756	11.737134	11.694676
14	0.33	RG	90	752	3-5-7	74.0	11.725269	11.719474	11.708160
14	0.33	RG	90	752	3-5-7	99.0	11.727270	11.721433	11.710179
14	0.33	RG	90	752	3-5-7	128.0	11.728949	11.723230	11.711778
14	0.33	RG	90	752	3-5-7	144.0	11.730236	11.724433	11.713106

15	0.53	RG	90	508	1-3-4	70.0	11.666280	11.701981	11.737328
15	0.53	RG	90	508	1-3-4	106.0	11.668461	11.704049	11.739514
15	0.53	RG	90	508	1-3-4	120.0	11.670095	11.705816	11.741215
15	0.53	RG	90	508	1-3-4	140.0	11.672036	11.707769	11.742905
15	0.53	RG	90	508	2-7-8	74.0	11.712359	11.718599	11.748383
15	0.53	RG	90	508	2-7-8	99.0	11.714649	11.720796	11.750783
15	0.53	RG	90	508	2-7-8	128.0	11.716331	11.723501	11.752558
15	0.53	RG	90	508	2-7-8	144.0	11.717425	11.723849	11.753794
16	0.45	RG	90	564	1-2-5	78.0	11.712110	11.685233	11.672970
16	0.45	RG	90	564	1-2-5	104.0	11.714081	11.687015	11.675046
16	0.45	RG	90	564	1-2-5	122.0	11.715060	11.687991	11.676043
16	0.45	RG	90	564	1-2-5	140.0	11.716654	11.689733	11.677614
16	0.45	RG	90	564	3-4-7	75.0	11.710605	11.700979	11.6512
16	0.45	RG	90	564	3-4-7	108.0	11.713129	11.703720	11.6539
16	0.45	RG	90	564	3-4-7	125.0	11.714304	11.704835	11.655375
16	0.45	RG	90	564	3-4-7	140.5	11.715616	11.706048	11.656455
17	0.33	RG	90	752	1-2-3	78.0	11.673490	11.700879	11.724848
17	0.33	RG	90	752	1-2-3	104.0	11.675506	11.703203	11.726490
17	0.33	RG	90	752	1-2-3	122.0	11.676440	11.704283	11.727459
17	0.33	RG	90	752	1-2-3	140.0	11.677985	11.707954	11.729098
17	0.33	RG	90	752	5-7-8	75.0	11.661718	11.722040	11.682914
17	0.33	RG	90	752	5-7-8	108.0	11.664685	11.724703	11.68545
17	0.33	RG	90	752	5-7-8	125.0	11.665436	11.725800	11.686351
17	0.33	RG	90	752	5-7-8	140.5	11.666656	11.727034	11.687614
18	0.45	RG	90	564	1-2-5	76.0	11.660731	11.692008	11.674968
18	0.45	RG	90	564	1-2-5	104.0	11.663100	11.693453	11.677169
18	0.45	RG	90	564	1-2-5	122.0	11.664278	11.695598	11.678324
18	0.45	RG	90	564	1-2-5	142.0	11.665869	11.697194	11.680051
18	0.45	RG	90	564	3-4-6	74.0	11.678944	11.649665	11.652153
18	0.45	RG	90	564	3-4-6	100.0	11.680981	11.652020	11.654330
18	0.45	RG	90	564	3-4-6	125.0	11.682971	11.653918	11.656085
18	0.45	RG	90	564	3-4-6	140.0	11.683788	11.654396	11.656780
19	0.53	DL	90	508	2-5-6	82.0	11.668398	11.673100	11.645266
19	0.53	DL	90	508	2-5-6	106.0	11.670128	11.674879	11.64696
19	0.53	DL	90	508	2-5-6	122.0	11.671328	11.676051	11.648064
19	0.53	DL	90	508	2-5-6	141.5	11.672631	11.677563	11.649589
19	0.53	DL	90	508	1-3-8	74.0	11.647626	11.656546	11.704311
19	0.53	DL	90	508	1-3-8	100.0	11.649598	11.658523	11.706059
19	0.53	DL	90	508	1-3-8	125.0	11.651281	11.660238	11.707654
19	0.53	DL	90	508	1-3-8	140.0	11.651953	11.660894	11.708256
20	0.33	DL	28	752	3-7-8	77.0	11.728236	11.717085	11.716115
20	0.33	DL	28	752	3-7-8	100.0	11.729886	11.718706	11.717278
20	0.33	DL	28	752	3-7-8	122.0	11.731301	11.720074	11.718760
20	0.33	DL	28	752	3-7-8	142.0	11.732908	11.721636	11.720199

```
20  0.33 DL 28 752 1-4-5  74.0  11.715641 11.712993 11.689728
20  0.33 DL 28 752 1-4-5 103.0  11.717345 11.714698 11.691553
20  0.33 DL 28 752 1-4-5 130.0  11.719136 11.716171 11.693218
20  0.33 DL 28 752 1-4-5 143.0  11.720238 11.717388 11.694293

21  0.53 DL 28 508 4-6-7  74.0  11.659873 11.733969 11.718933
21  0.53 DL 28 508 4-6-7 101.0  11.661469 11.735714 11.720590
21  0.53 DL 28 508 4-6-7 122.0  11.662930 11.737025 11.721906
21  0.53 DL 28 508 4-6-7 141.0  11.664481 11.739510 11.723374

21  0.53 DL 28 508 1-3-8  74.0  11.715518 11.737404 11.731645
21  0.53 DL 28 508 1-3-8 106.0  11.716878 11.739026 11.733295
21  0.53 DL 28 508 1-3-8 127.0  11.718405 11.740589 11.734706
21  0.53 DL 28 508 1-3-8 143.0  11.719811 11.741925 11.735994

22  0.45 DL 90 564 4-6-7  78.0  11.732960 11.703264 11.724630
22  0.45 DL 90 564 4-6-7 104.0  11.734595 11.705024 11.726343
22  0.45 DL 90 564 4-6-7 123.0  11.735763 11.706223 11.727499
22  0.45 DL 90 564 4-6-7 140.0  11.736990 11.707603 11.728815

22  0.45 DL 90 564 2-3-5  74.0  11.734014 11.690328 11.730130
22  0.45 DL 90 564 2-3-5 106.0  11.735483 11.691806 11.731216
22  0.45 DL 90 564 2-3-5 127.0  11.736930 11.693446 11.732651
22  0.45 DL 90 564 2-3-5 143.0  11.738301 11.694840 11.733959

23  0.33 DL 90 752 1-5-6  75.0  11.719910 11.748233 11.771068
23  0.33 DL 90 752 1-4-6 104.0  11.721606 11.749756 11.772829
23  0.33 DL 90 752 1-5-6 128.0  11.723364 11.751329 11.774583
23  0.33 DL 90 752 1-5-6 142.0  11.724325 11.752243 11.775516

23  0.33 DL 90 752 2-3-7  82.0  11.764124 11.747821 11.746870
23  0.33 DL 90 752 2-3-7 106.0  11.765806 11.749670 11.748658
23  0.33 DL 90 752 2-3-7 124.0  11.766946 11.750958 11.749916
23  0.33 DL 90 752 2-3-7 140.0  11.768066 11.752083 11.751125

24  0.45 DL 90 564 4-5-6  70.0  11.725441 11.752840  11.72928
24  0.45 DL 90 564 4-5-6 107.0  11.728049 11.755445 11.731931
24  0.45 DL 90 564 4-5-6 122.0  11.729148 11.756578 11.732996
24  0.45 DL 90 564 4-5-6 143.0  11.730540 11.758100 11.734388

24  0.45 DL 90 564 1-7-8  82.0  11.741986 11.721024 11.731008
24  0.45 DL 90 564 1-7-8 106.0  11.743829 11.722739 11.73277
24  0.45 DL 90 564 1-7-8 124.0  11.745196 11.724096 11.734046
24  0.45 DL 90 564 1-7-8 140.0  11.746310 11.725321 11.735344
```

APPENDIX D

LENGTH READINGS OF OVEN-DRIED LABORATORY CONCRETE SPECIMENS

COEFFICIENT OF THERMAL EXPANSION
DRY SPECIMENS
LABORATORY STUDY

LEGEND

COLUMN A = BATCH NUMBER
COLUMN B = WATER-CEMENT RATIO
COLUMN C = TYPE OF AGGREGATE
COLUMN D = MOIST-CURING DURATION (DAYS)
COLUMN E = CEMENT CONTENT (lb/cy)
COLUMN F = SPECIMEN IDENTIFICATION NUMBERS (SEPARATED BY DASHES)
COLUMN G = SPECIMEN TEMPERATURE
COLUMN H = LENGTH OF FIRST SPECIMEN IN COLUMN F
COLUMN I = LENGTH OF SECOND SPECIMEN IN COLUMN F
COLUMN J = LENGTH OF THIRD SPECIMEN IN COLUMN F

A	B	C	D	E	F	G	H	I	J
1	0.53	BL	28	564	3-6	82.0	11.849476	11.840856	
1	0.53	BL	28	564	3-6	104.0	11.850830	11.842109	
1	0.53	BL	28	564	3-6	124.0	11.843385	11.843385	
1	0.53	BL	28	564	3-6	140.0	11.852516	11.844159	
1	0.53	BL	28	564	4	86.0	11.806335		
1	0.53	BL	28	564	4	106.5	11.807480		
1	0.53	BL	28	564	4	123.0	11.808836		
1	0.53	BL	28	564	4	140.0	11.810234		
1	0.53	BL	90	564	1-5-7	74.0	11.820670	11.821095	11.785166
1	0.53	BL	90	564	1-5-7	104.0	11.833290	11.823623	11.787700
1	0.53	BL	90	564	1-5-7	122.0	11.824334	11.814631	11.788586
1	0.53	BL	90	564	1-5-7	142.0	11.825730	11.816024	11.789668
2	0.53	BL	28	508	2-1-6	82.0	11.847353	11.866634	11.868629
2	0.53	BL	28	508	2-1-6	104.0	11.848805	11.867844	11.870204
2	0.53	BL	28	508	2-1-6	124.0	11.849939	11.869056	11.871491
2	0.53	BL	28	508	2-1-6	140.0	11.850900	11.870101	11.872523
2	0.53	BL	90	508	3-7-9	81.0	11.704571	11.722589	11.680279
2	0.53	BL	90	508	3-7-9	108.0	11.706204	11.724256	11.682073
2	0.53	BL	90	508	3-7-9	124.0	11.707050	11.725385	11.683161
2	0.53	BL	90	508	3-7-9	140.0	11.708191	11.726385	11.684060
3	0.45	BL	28	658	1-2-7	77.0	11.842821	11.793568	11.873136
3	0.45	BL	28	658	1-2-7	104.0	11.844308	11.795120	11.874764
3	0.45	BL	28	658	1-2-7	122.0	11.845611	11.796336	11.876100
3	0.45	BL	28	658	1-2-7	140.0	11.846655	11.797474	11.877463
3	0.45	BL	90	658	3-5-8	80.0	11.788295	11.789418	11.840765
3	0.45	BL	90	658	3-5-8	108.0	11.790125	11.790340	11.842629
3	0.45	BL	90	658	3-5-8	124.0	11.791108	11.791529	11.843915
4	0.45	BL	28	564	2-4-8	74.0	11.800873	11.779251	11.723019

```
4  0.45 BL 28 564 2-4-8 104.0  11.803491 11.781706 11.725604
4  0.45 BL 28 564 2-4-8 122.0  11.804421 11.782720 11.726843
4  0.45 BL 28 564 2-4-8 142.0  11.805733 11.784096 11.728269

4  0.45 BL 90 564 5-6-7  78.0  11.767949 11.685463 11.718603
4  0.45 BL 90 564 5-6-7 107.0  11.769914 11.687226 11.720533
4  0.45 BL 90 564 5-6-7 121.0  11.771079 11.688386 11.721506
4  0.45 BL 90 564 5-6-7 142.5  11.772774 11.690059 11.723100

5  0.38 BL 28 658 3-5-7  81.0  11.838435 11.832123 11.834618
5  0.38 BL 28 658 3-5-7 108.0  11.840146 11.833824 11.836326
5  0.38 BL 28 658 3-5-7 124.0  11.840971 11.834710 11.837389
5  0.38 BL 28 658 3-5-7 140.0  11.841976 11.835850 11.838361

5  0.38 BL 28 658 1-4-8  80.0  11.821115 11.808876 11.832780
5  0.38 BL 28 658 1-4-8 102.0  11.822611 11.810443 11.83426
5  0.38 BL 28 658 1-4-8 121.5  11.824001 11.811658 11.835546
5  0.38 BL 28 658 1-4-8 141.0  11.826373 11.813086 11.836786

6  0.38 BL 28 658 1-3-8  76.0  11.821891 11.878823 11.869981
6  0.38 BL 28 658 1-3-8 104.0  11.823783 11.880850 11.871746
6  0.38 BL 28 658 1-3-8 122.0  11.824853 11.881864 11.872843
6  0.38 BL 28 658 1-3-8 140.0  11.825979 11.883044 11.873820

6  0.38 BL 28 658 4-5-8  78.5  11.830465 11.870353 11.815085
6  0.38 BL 28 658 4-5-8 107.0  11.832465 11.872483 11.817079
6  0.38 BL 28 658 4-5-8 121.5  11.834418 11.874059 11.818841
6  0.38 BL 28 658 4-5-8 140.0  11.834711 11.874516 11.819054

7  0.45 BL 90 564 1-4-5  76.0  11.859744 11.830298 11.814050
7  0.45 BL 90 564 1-4-5 102.0  11.861343 11.832071 11.816104
7  0.45 BL 90 564 1-4-5 126.0  11.862614 11.833295 11.817376
7  0.45 BL 90 564 1-4-5 140.0  11.863438 11.833971 11.818191

7  0.45 BL 90 564 3-6-8  89.0  11.785268 11.838798 11.835634
7  0.45 BL 90 564 3-6-8 101.0  11.786251 11.839590 11.836375
7  0.45 BL 90 564 3-6-8 125.0  11.787791 11.841078 11.837844
7  0.45 BL 90 564 3-6-8 142.0  11.789166 11.842310 11.839033

8  0.53 BL 28 508 1-4-5  76.0  11.800814 11.883750 11.833160
8  0.53 BL 28 508 1-4-5 102.0  11.802481 11.885764 11.835095
8  0.53 BL 28 508 1-4-5 126.0  11.803853 11.887189 11.836576
8  0.53 BL 28 508 1-4-5 140.0  11.804573 11.887951 11.837213

8  0.53 BL 28 508 2-3-6  82.0  11.854529 11.843789 11.773046
8  0.53 BL 28 508 2-3-6 104.5  11.856165 11.845454 11.774815
8  0.53 BL 28 508 2-3-6 123.5  11.857474 11.846848 11.776218
8  0.53 BL 28 508 2-3-6 142.0  11.858801 11.847944 11.777259

9  0.45 BL 90 658 1-2-6  79.0  11.863079 11.817699 11.809580
9  0.45 BL 90 658 1-2-6 107.0  11.864996 11.819719 11.811063
9  0.45 BL 90 658 1-2-6 122.0  11.866050 11.820700 11.812066
9  0.45 BL 90 658 1-2-6 140.0  11.867296 11.821999 11.813385
```

9	0.45	BL	90	658	3-7-8	78.0	11.788934	11.756099	11.788634
9	0.45	BL	90	658	3-7-8	105.0	11.790665	11.757991	11.790290
9	0.45	BL	90	658	3-7-8	123.0	11.791621	11.759024	11.791175
9	0.45	BL	90	658	3-7-8	141.5	11.792716	11.760015	11.792261
10	0.33	BL	90	752	2-5-7	80.0	11.766980	11.794559	11.742430
10	0.33	BL	90	752	2-5-7	108.0	11.768940	11.796484	11.744525
10	0.33	BL	90	752	2-5-7	124.0	11.769993	11.797516	11.745785
10	0.33	BL	90	752	1-3-6	85.0	11.785028	11.769554	11.776683
10	0.33	BL	90	752	1-3-6	106.5	11.786345	11.770871	11.777984
10	0.33	BL	90	752	1-3-6	123.0	11.787620	11.772158	11.779184
10	0.33	BL	90	752	1-3-6	140.0	11.789168	11.773678	11.780518
11	0.53	BL	28	564	4-6-7	84.0	11.776558	11.718626	11.73354
11	0.53	BL	28	564	4-6-7	106.0	11.778993	11.720151	11.73540
11	0.53	BL	28	564	4-6-7	122.0	11.780233	11.721394	11.736619
11	0.53	BL	28	564	4-6-7	145.0	11.781401	11.722589	11.737790
11	0.53	BL	28	564	1-3-8	86.0	11.729701	11.725040	11.754996
11	0.53	BL	28	564	1-3-8	106.5	11.730876	11.726455	11.756303
11	0.53	BL	28	564	1-3-8	123.0	11.732144	11.727601	11.757403
11	0.53	BL	28	564	1-3-8	140.0	11.733583	11.728925	11.758879
12	0.33	BL	90	752	4-7-8	84.0	11.761938	11.754293	11.721429
12	0.33	BL	90	752	4-7-8	106.0	11.763603	11.755905	11.722914
12	0.33	BL	90	752	4-7-8	122.0	11.765000	11.757293	11.724276
12	0.33	BL	90	752	4-7-8	145.0	11.766221	11.758660	11.725606
12	0.33	BL	90	752	1-5-6	83.0	11.765868	11.741974	11.744814
12	0.33	BL	90	752	1-5-6	106.0	11.767199	11.743428	11.746054
12	0.33	BL	90	752	1-5-6	123.5	11.768436	11.744560	11.747174
12	0.33	BL	90	752	1-5-6	140.0	11.769743	11.745879	11.748268
13	0.53	RG	90	508	1-3-5	74.5	11.690765	11.737563	11.735139
13	0.53	RG	90	508	1-3-5	104.0	11.693424	11.740236	11.737745
13	0.53	RG	90	508	1-3-5	122.0	11.694950	11.741779	11.739154
13	0.53	RG	90	508	1-3-5	140.0	11.696598	11.743424	11.740811
13	0.53	RG	90	508	2-4-6	83.0	11.716850	11.682169	11.709366
13	0.53	RG	90	508	2-4-6	106.0	11.718776	11.683831	11.711224
13	0.53	RG	90	508	2-4-6	123.5	11.720461	11.685395	11.712624
13	0.53	RG	90	508	2-4-6	140.0	11.722024	11.686714	11.714058
14	0.33	RG	28	752	4-6-8	74.0	11.626625	11.725781	11.683563
14	0.33	RG	28	752	4-6-8	106.0	11.629315	11.728463	11.686226
14	0.33	RG	28	752	4-6-8	122.0	11.631080	11.730140	11.687563
14	0.33	RG	28	752	4-6-8	142.0	11.632606	11.731903	11.689160
14	0.33	RG	90	752	3-5-7	83.0	11.723068	11.717263	11.706080
14	0.33	RG	90	752	3-5-7	105.5	11.724610	11.718985	11.707723
14	0.33	RG	90	752	3-5-7	123.0	11.725706	11.720101	11.708709
14	0.33	RG	90	752	3-5-7	141.0	11.726971	11.721371	11.709966

15	0.53	RG	90	508	1-3-4	74.0	11.661419	11.696785	11.732560
15	0.53	RG	90	508	1-3-4	106.0	11.664095	11.699556	11.735479
15	0.53	RG	90	508	1-3-4	122.0	11.665889	11.701099	11.736865
15	0.53	RG	90	508	1-3-4	142.0	11.667381	11.702911	11.738391
15	0.53	RG	90	508	2-7-8	83.0	11.709850	11.715830	11.746135
15	0.53	RG	90	508	2-7-8	105.5	11.711785	11.717899	11.748100
15	0.53	RG	90	508	2-7-8	123.0	11.713109	11.719084	11.749304
15	0.53	RG	90	508	2-7-8	141.0	11.714346	11.720520	11.750718
16	0.45	RG	90	564	1-2-5	82.0	11.707646	11.680759	11.669144
16	0.45	RG	90	564	1-2-5	106.0	11.709968	11.683235	11.671445
16	0.45	RG	90	564	1-2-5	118.0	11.711508	11.684800	11.672876
16	0.45	RG	90	564	1-2-5	140.5	11.712830	11.685930	11.674084
16	0.45	RG	90	564	3-4-7	82.0	11.707533	11.698105	11.648415
16	0.45	RG	90	564	3-4-7	103.0	11.709650	11.700049	11.650480
16	0.45	RG	90	564	3-4-7	125.0	11.711528	11.702175	11.652560
16	0.45	RG	90	564	3-4-7	143.0	11.712705	11.703155	11.653231
17	0.33	RG	90	752	1-2-3	82.0	11.668776	11.697013	11.720259
17	0.33	RG	90	752	1-2-3	106.0	11.671055	11.699150	11.722444
17	0.33	RG	90	752	1-2-3	118.0	11.672644	11.700766	11.723998
17	0.33	RG	90	752	1-2-3	140.5	11.673993	11.701956	11.725066
17	0.33	RG	90	752	5-7-8	82.0	11.658830	11.719503	11.680094
17	0.33	RG	90	752	5-7-8	103.0	11.660738	11.721583	11.681946
17	0.33	RG	90	752	5-7-8	125.0	11.662625	11.723368	11.683674
17	0.33	RG	90	752	5-7-8	143.0	11.663499	11.724274	11.684639
18	0.45	RG	90	564	1-2-5	78.0	11.656268	11.687328	11.670429
18	0.45	RG	90	564	1-2-5	107.0	11.658691	11.689850	11.672775
18	0.45	RG	90	564	1-2-5	121.0	11.660156	11.691181	11.674014
18	0.45	RG	90	564	1-2-5	142.5	11.662226	11.693255	11.676044
18	0.45	RG	90	564	3-4-6	82.5	11.676909	11.647825	11.650241
18	0.45	RG	90	564	3-4-6	104.5	11.678815	11.649740	11.652208
18	0.45	RG	90	564	3-4-6	123.0	11.680603	11.651380	11.653910
18	0.45	RG	90	564	3-4-6	141.0	11.681785	11.652661	11.654930
19	0.53	DL	90	508	2-5-6	82.0	11.666198	11.670783	11.643618
19	0.53	DL	90	508	2-5-6	105.0	11.667991	11.672501	11.645275
19	0.53	DL	90	508	2-5-6	121.5	11.669176	11.673755	11.646320
19	0.53	DL	90	508	2-5-6	145.0	11.670836	11.675419	11.648393
19	0.53	DL	90	508	1-3-8	82.5	11.647005	11.656061	11.703826
19	0.53	DL	90	508	1-3-8	104.5	11.648650	11.657683	11.705410
19	0.53	DL	90	508	1-3-8	123.0	11.650369	11.659174	11.706561
19	0.53	DL	90	508	1-3-8	141.0	11.651448	11.660251	11.707556
20	0.33	DL	28	752	3-7-8	80.0	11.725694	11.714171	11.713109
20	0.33	DL	28	752	3-7-8	102.0	11.727266	11.715789	11.714738
20	0.33	DL	28	752	3-7-8	121.5	11.728695	11.717106	11.715906
20	0.33	DL	28	752	3-7-8	141.0	11.729929	11.718419	11.717158

20	0.33	DL	28	752	1-4-5	84.5	11.714013	11.711139	11.688025
20	0.33	DL	28	752	1-4-5	105.5	11.715511	11.712728	11.689645
20	0.33	DL	28	752	1-4-5	122.0	11.716486	11.713973	11.690900
20	0.33	DL	28	752	1-4-5	141.5	11.717806	11.715405	11.692249
21	0.53	DL	28	508	4-6-7	78.5	11.657120	11.730984	11.716469
21	0.53	DL	28	508	4-6-7	107.0	11.659216	11.733195	11.718591
21	0.53	DL	28	508	4-6-7	121.5	11.660958	11.725019	11.720213
21	0.53	DL	28	508	4-6-7	140.0	11.661541	11.735560	11.720600
21	0.53	DL	28	508	1-3-8	78.0	11.712879	11.735080	11.729088
21	0.53	DL	28	508	1-3-8	101.5	11.714566	11.736765	11.730895
21	0.53	DL	28	508	1-3-8	120.0	11.715331	11.737461	11.731744
21	0.53	DL	28	508	1-3-8	141.0	11.716979	11.739481	11.733728
22	0.45	DL	90	564	4-6-7	74.5	11.728978	11.699490	11.720719
22	0.45	DL	90	564	4-6-7	106.5	11.731243	11.701936	11.723145
22	0.45	DL	90	564	4-6-7	126.0	11.732775	11.703450	11.724544
22	0.45	DL	90	564	4-6-7	142.0	11.733914	11.704513	11.725574
22	0.45	DL	90	564	2-3-5	78.0	11.731501	11.687825	11.727185
22	0.45	DL	90	564	2-3-5	101.5	11.733089	11.689561	11.728951
22	0.45	DL	90	564	2-3-5	120.0	11.733738	11.690223	11.729698
22	0.45	DL	90	564	2-3-5	141.0	11.735423	11.692026	11.731661
23	0.33	DL	90	752	1-5-6	89.0	11.718095	11.745933	11.769393
23	0.33	DL	90	752	1-4-6	101.0	11.718956	11.746728	11.770236
23	0.33	DL	90	752	1-5-6	125.0	11.720863	11.748823	11.771951
23	0.33	DL	90	752	1-5-6	142.0	11.721838	11.749801	11.772896
23	0.33	DL	90	752	2-3-7	78.0	11.761168	11.745078	11.744158
23	0.33	DL	90	752	2-3-7	110.0	11.763280	11.747278	11.746345
23	0.33	DL	90	752	2-3-7	122.5	11.764083	11.748125	11.747258
23	0.33	DL	90	752	2-3-7	140.0	11.765326	11.749470	11.748590
24	0.45	DL	90	564	4-5-6	82.0	11.723201	11.750796	11.727156
24	0.45	DL	90	564	4-5-6	104.5	11.725121	11.752610	11.729068
24	0.45	DL	90	564	4-5-6	123.5	11.726614	11.754233	11.730594
24	0.45	DL	90	564	4-5-6	142.0	11.728039	11.755550	11.731681
24	0.45	DL	90	564	1-7-8	78.0	11.739303	11.717873	11.728006
24	0.45	DL	90	564	1-7-8	110.0	11.741238	11.720015	11.730239
24	0.45	DL	90	564	1-7-8	122.5	11.741984	11.720931	11.731116
24	0.45	DL	90	564	1-7-8	140.0	11.743095	11.722095	11.732396

APPENDIX E

LENGTH READINGS OF PARTIALLY-SATURATED LABORATORY CONCRETE SPECIMENS

COEFFICIENT OF MOISTURE EXPANSION
LABORATORY STUDY

LEGEND

COLUMN A = BATCH NUMBER
COLUMN B = WATER-CEMENT RATIO
COLUMN C = TYPE OF AGGREGATE
COLUMN D = MOIST-CURING DURATION (DAYS)
COLUMN E = CEMENT CONTENT (lb/cy)
COLUMN F = AMBIENT TEMPERATURE (OF)
COLUMN G = SPECIMEN IDENTIFICATION NUMBER
COLUMN H = WEIGHT OF CONCRETE SPECIMEN
COLUMN I = CHANGE IN WEIGHT OF SPECIMEN WITH RESPECT TO OVEN-DRIED WEIGHT
COLUMN J = MEASURED LENGTH OF CONCRETE SPECIMEN (INCHES)
COLUMN K = CHANGE IN TEMP. FROM REFERENCE TEMP.
COLUMN L = LENGTH OF SPECIMEN CORRECTED FOR TEMP.

A	B	C	D	E	F	G	H	I	J	K	L
1	0.53	BL	28	564	77.5	3	3618.7	121.9	11.853831	-0.5	11.853828
1	0.53	BL	28	564	77.5	3	3549.4	52.6	11.853829	-0.5	11.853826
1	0.53	BL	28	564	77.0	3	3530.8	34.0	11.853739	0.0	11.853739
1	0.53	BL	28	564	77.0	3	3496.8	0.0	11.853488	0.0	11.853488
1	0.53	BL	28	564	77.5	6	3601.4	119.8	11.854559	-0.5	11.854556
1	0.53	BL	28	564	77.5	6	3536.9	55.3	11.845443	-0.5	11.845440
1	0.53	BL	28	564	77.0	6	3515.9	34.3	11.845446	0.0	11.845446
1	0.53	BL	28	564	77.0	6	3481.6	0.0	11.845130	0.0	11.845130
1	0.53	BL	28	564	74.0	4	3558.2	128.8	11.809544	3.0	11.809561
1	0.53	BL	28	564	69.5	4	3525.1	95.7	11.809340	7.5	11.809382
1	0.53	BL	28	564	72.0	4	3490.8	61.4	11.809184	5.0	11.809212
1	0.53	BL	28	564	70.0	4	3429.4	0.0	11.807984	7.0	11.808023
1	0.53	BL	90	564	74.0	1	3621.3	110.6	11.825045	3.0	11.825062
1	0.53	BL	90	564	76.0	1	3565.4	54.7	11.824880	1.0	11.824886
1	0.53	BL	90	564	74.0	1	3537.7	27.0	11.824401	3.0	11.824418
1	0.53	BL	90	564	73.5	1	3519.7	9.0	11.823611	3.5	11.823630
1	0.53	BL	90	564	79.0	1	3510.7	0.0	11.823439	-2.0	11.823428
1	0.53	BL	90	564	74.0	5	3629.8	102.5	11.814928	3.0	11.814945
1	0.53	BL	90	564	76.0	5	3579.3	52.0	11.813086	1.0	11.813092
1	0.53	BL	90	564	74.0	5	3553.7	26.4	11.812791	3.0	11.812808
1	0.53	BL	90	564	73.5	5	3536.4	9.1	11.811773	3.5	11.811792
1	0.53	BL	90	564	79.0	5	3527.3	0.0	11.811595	-2.0	11.811584
1	0.53	BL	90	564	74.0	7	3624.0	110.8	11.785708	3.0	11.785725
1	0.53	BL	90	564	76.0	7	3566.9	53.7	11.785686	1.0	11.785692
1	0.53	BL	90	564	74.0	7	3540.3	27.1	11.785585	3.0	11.785602
1	0.53	BL	90	564	73.5	7	3522.1	8.9	11.785031	3.5	11.785050
1	0.53	BL	90	564	79.0	7	3513.2	0.0	11.784636	-2.0	11.784625

```
2  0.53 BL 28 508 77.5  1 3583.9 114.8 11.851244 -0.5 11.851241
2  0.53 BL 28 508 77.5  1 3523.5  54.4 11.851234 -0.5 11.851231
2  0.53 BL 28 508 77.0  1 3504.4  35.3 11.851205  0.0 11.851205
2  0.53 BL 28 508 77.0  1 3469.1   0.0 11.850886  0.0 11.850886

2  0.53 BL 28 508 77.5  2 3584.2 122.1 11.878913 -0.5 11.878910
2  0.53 BL 28 508 77.5  2 3523.9  61.8 11.870065 -0.5 11.870062
2  0.53 BL 28 508 77.0  2 3501.7  39.6 11.870019  0.0 11.870019
2  0.53 BL 28 508 77.0  2 3462.1   0.0 11.869751  0.0 11.869751

2  0.53 BL 28 508 77.5  6 3717.7 112.4 11.879905 -0.5 11.879902
2  0.53 BL 28 508 77.5  6 3671.5  66.2 11.871049 -0.5 11.871046
2  0.53 BL 28 508 77.0  6 3653.1  47.8 11.871050  0.0 11.871050
2  0.53 BL 28 508 77.0  6 3605.3   0.0 11.870999  0.0 11.870999

2  0.53 BL 90 508 74.5  3 3631.2 224.3 11.708033  2.5 11.708047
2  0.53 BL 90 508 74.0  3 3575.7 168.8 11.706974  3.0 11.706991
2  0.53 BL 90 508 72.5  3 3528.9 122.0 11.706941  4.5 11.706966
2  0.53 BL 90 508 73.5  3 3498.7  91.8 11.706611  3.5 11.706630
2  0.53 BL 90 508 81.0  3 3406.9   0.0 11.704571 -4.0 11.704549

2  0.53 BL 90 508 74.5  7 3630.0 229.2 11.725608  2.5 11.725622
2  0.53 BL 90 508 74.0  7 3574.0 173.2 11.725156  3.0 11.725173
2  0.53 BL 90 508 72.5  7 3520.2 119.4 11.725116  4.5 11.725141
2  0.53 BL 90 508 73.5  7 3491.1  90.3 11.724635  3.5 11.724654
2  0.53 BL 90 508 81.0  7 3400.8   0.0 11.722589 -4.0 11.722567

2  0.53 BL 90 508 74.5  9 3672.8 228.1 11.683303  2.5 11.683317
2  0.53 BL 90 508 74.0  9 3613.6 168.9 11.682636  3.0 11.682653
2  0.53 BL 90 508 72.5  9 3561.5 116.8 11.683049  4.5 11.683074
2  0.53 BL 90 508 73.5  9 3532.9  88.2 11.682201  3.5 11.682220
2  0.53 BL 90 508 81.0  9 3444.7   0.0 11.680279 -4.0 11.680257

3  0.45 BL 28 658 77.5  1 3763.8  89.8 11.848354 -0.5 11.848351
3  0.45 BL 28 658 77.5  1 3724.2  50.2 11.848330 -0.5 11.848327
3  0.45 BL 28 658 77.0  1 3709.5  35.5 11.848316  0.0 11.848316
3  0.45 BL 28 658 77.0  1 3674.0   0.0 11.848231  0.0 11.848231

3  0.45 BL 28 658 77.5  2 3709.9 102.9 11.798909 -0.5 11.798906
3  0.45 BL 28 658 77.5  2 3662.4  55.4 11.798881 -0.5 11.798878
3  0.45 BL 28 658 77.0  2 3644.8  37.8 11.798828  0.0 11.798828
3  0.45 BL 28 658 77.0  2 3607.0   0.0 11.798814  0.0 11.798814

3  0.45 BL 28 658 77.5  7 3771.8 103.0 11.878694 -0.5 11.878691
3  0.45 BL 28 658 77.5  7 3724.9  56.1 11.878591 -0.5 11.878588
3  0.45 BL 28 658 77.0  7 3707.1  38.3 11.878456  0.0 11.878456
3  0.45 BL 28 658 77.0  7 3668.8   0.0 11.878299  0.0 11.878299

3  0.45 BL 90 658 74.0  3 3756.7 258.9 11.792458  3.0 11.792475
3  0.45 BL 90 658 67.0  3 3712.3 214.5 11.790899 10.0 11.790955
3  0.45 BL 90 658 72.0  3 3546.0  48.2 11.789703  5.0 11.789731
3  0.45 BL 90 658 76.0  3 3522.4  24.6 11.789328  1.0 11.789334
3  0.45 BL 90 658 80.0  3 3497.8   0.0 11.788295 -3.0 11.788278
```

3	0.45	BL	90	658	74.0	5	3802.9	259.8	11.792125	3.0	11.792142
3	0.45	BL	90	658	67.0	5	3757.0	213.9	11.790831	10.0	11.790887
3	0.45	BL	90	658	72.0	5	3593.2	50.1	11.789775	5.0	11.789803
3	0.45	BL	90	658	76.0	5	3569.1	26.0	11.789425	1.0	11.789431
3	0.45	BL	90	658	80.0	5	3543.1	0.0	11.789418	-3.0	11.789401
3	0.45	BL	90	658	74.0	8	3807.8	259.4	11.844740	3.0	11.844757
3	0.45	BL	90	658	67.0	8	3764.9	216.5	11.843416	10.0	11.843472
3	0.45	BL	90	658	72.0	8	3599.8	51.4	11.842000	5.0	11.842028
3	0.45	BL	90	658	76.0	8	3576.0	27.6	11.841750	1.0	11.841756
3	0.45	BL	90	658	80.0	8	3548.4	0.0	11.840765	-3.0	11.840748
4	0.45	BL	28	564	74.0	2	3789.5	246.4	11.805200	3.0	11.805217
4	0.45	BL	28	564	76.0	2	3741.0	197.9	11.805040	1.0	11.805046
4	0.45	BL	28	564	74.0	2	3718.0	174.9	11.804640	3.0	11.804657
4	0.45	BL	28	564	73.5	2	3710.1	167.0	11.803950	3.5	11.803969
4	0.45	BL	28	564	79.0	2	3695.9	152.8	11.803930	-2.0	11.803919
4	0.45	BL	28	564	74.0	2	3543.1	0.0	11.800873	3.0	11.800890
4	0.45	BL	28	564	74.0	4	3791.1	244.4	11.783778	3.0	11.783795
4	0.45	BL	28	564	76.0	4	3746.3	199.6	11.783500	1.0	11.783506
4	0.45	BL	28	564	74.0	4	3724.1	177.4	11.783154	3.0	11.783171
4	0.45	BL	28	564	73.5	4	3703.6	156.9	11.782381	3.5	11.782400
4	0.45	BL	28	564	79.0	4	3702.5	155.8	11.782445	-2.0	11.782434
4	0.45	BL	28	564	74.0	4	3546.7	0.0	11.779251	3.0	11.779268
4	0.45	BL	28	564	74.0	8	3747.3	241.6	11.727326	3.0	11.727343
4	0.45	BL	28	564	76.0	8	3710.1	204.4	11.727309	1.0	11.727315
4	0.45	BL	28	564	74.0	8	3689.7	184.0	11.727026	3.0	11.727043
4	0.45	BL	28	564	73.5	8	3675.0	169.3	11.726354	3.5	11.726373
4	0.45	BL	28	564	79.0	8	3666.4	160.7	11.726375	-2.0	11.726364
4	0.45	BL	28	564	74.0	8	3505.7	0.0	11.723019	3.0	11.723036
4	0.45	BL	90	564	76.0	5	3766.5	248.1	11.772154	1.0	11.772160
4	0.45	BL	90	564	73.0	5	3710.1	191.7	11.771308	4.0	11.771330
4	0.45	BL	90	564	75.0	5	3676.8	158.4	11.771615	2.0	11.771626
4	0.45	BL	90	564	74.5	5	3631.1	112.7	11.770710	2.5	11.770724
4	0.45	BL	90	564	78.0	5	3518.4	0.0	11.767949	-1.0	11.767943
4	0.45	BL	90	564	76.0	6	3790.5	249.8	11.689433	1.0	11.689439
4	0.45	BL	90	564	73.0	6	3743.8	203.1	11.688558	4.0	11.688580
4	0.45	BL	90	564	75.0	6	3714.3	173.6	11.688929	2.0	11.688940
4	0.45	BL	90	564	74.5	6	3662.8	122.1	11.687908	2.5	11.687922
4	0.45	BL	90	564	78.0	6	3540.7	0.0	11.685463	-1.0	11.685457
4	0.45	BL	90	564	76.0	7	3782.4	247.3	11.722700	1.0	11.722706
4	0.45	BL	90	564	73.0	7	3725.4	190.3	11.721940	4.0	11.721962
4	0.45	BL	90	564	75.0	7	3697.2	162.1	11.722158	2.0	11.722169
4	0.45	BL	90	564	74.5	7	3652.3	117.2	11.721110	2.5	11.721124
4	0.45	BL	90	564	78.0	7	3535.1	0.0	11.718603	-1.0	11.718597
5	0.38	BL	28	658	74.5	3	3832.0	218.8	11.841665	2.5	11.841679
5	0.38	BL	28	658	74.0	3	3777.3	164.1	11.840528	3.0	11.840545
5	0.38	BL	28	658	72.5	3	3738.8	125.6	11.841143	4.5	11.841168

```
5  0.38 BL 28 658 73.5  3 3715.5 102.3 11.840800  3.5 11.840819
5  0.38 BL 28 658 81.0  3 3613.2   0.0 11.838435 -4.0 11.838413

5  0.38 BL 28 658 74.5  5 3813.8 216.4 11.835581  2.5 11.835595
5  0.38 BL 28 658 74.0  5 3765.7 168.3 11.834440  3.0 11.834457
5  0.38 BL 28 658 72.5  5 3727.8 130.4 11.835149  4.5 11.835174
5  0.38 BL 28 658 73.5  5 3701.7 104.3 11.834654  3.5 11.834673
5  0.38 BL 28 658 81.0  5 3597.4   0.0 11.832123 -4.0 11.832101

5  0.38 BL 28 658 74.5  7 3835.2 217.2 11.838748  2.5 11.838762
5  0.38 BL 28 658 74.0  7 3783.6 165.6 11.837138  3.0 11.837155
5  0.38 BL 28 658 72.5  7 3744.6 126.6 11.837810  4.5 11.837835
5  0.38 BL 28 658 73.5  7 3719.6 101.6 11.837223  3.5 11.837242
5  0.38 BL 28 658 81.0  7 3618.0   0.0 11.834618 -4.0 11.834596

5  0.38 BL 90 658 77.0  1 3876.2 228.5 11.824335  0.0 11.824335
5  0.38 BL 90 658 74.0  1 3848.1 200.4 11.823825  3.0 11.823842
5  0.38 BL 90 658 73.0  1 3824.1 176.4 11.823010  4.0 11.823032
5  0.38 BL 90 658 80.0  1 3647.7   0.0 11.821115 -3.0 11.821098

5  0.38 BL 90 658 77.0  4 3819.8 223.2 11.811698  0.0 11.811698
5  0.38 BL 90 658 74.0  4 3788.9 192.3 11.811028  3.0 11.811045
5  0.38 BL 90 658 73.0  4 3763.9 167.3 11.810106  4.0 11.810128
5  0.38 BL 90 658 80.0  4 3596.6   0.0 11.808876 -3.0 11.808859

5  0.38 BL 90 658 77.0  8 3792.6 220.1 11.835463  0.0 11.835463
5  0.38 BL 90 658 74.0  8 3767.4 194.9 11.835058  3.0 11.835075
5  0.38 BL 90 658 73.0  8 3748.4 175.9 11.834274  4.0 11.834296
5  0.38 BL 90 658 80.0  8 3572.5   0.0 11.832780 -3.0 11.832763

6  0.38 BL 28 658 74.0  1 3850.5 197.1 11.826215  3.0 11.826232
6  0.38 BL 28 658 76.0  1 3783.1 129.7 11.825874  1.0 11.825880
6  0.38 BL 28 658 75.0  1 3780.6 127.2 11.825649  2.0 11.825660
6  0.38 BL 28 658 76.0  1 3774.7 121.3 11.825346  1.0 11.825352
6  0.38 BL 28 658 77.0  1 3757.7 104.3 11.824864  0.0 11.824864
6  0.38 BL 28 658 77.0  1 3736.5  83.1 11.824435  0.0 11.824435
6  0.38 BL 28 658 76.0  1 3653.4   0.0 11.821891  1.0 11.821897

6  0.38 BL 28 658 74.0  3 3865.7 200.3 11.882474  3.0 11.882491
6  0.38 BL 28 658 76.0  3 3808.5 143.1 11.882448  1.0 11.882454
6  0.38 BL 28 658 75.0  3 3804.7 139.3 11.882355  2.0 11.882366
6  0.38 BL 28 658 76.0  3 3797.9 132.5 11.882135  1.0 11.882141
6  0.38 BL 28 658 77.0  3 3778.5 113.1 11.881698  0.0 11.881698
6  0.38 BL 28 658 77.0  3 3756.6  91.2 11.881428  0.0 11.881428
6  0.38 BL 28 658 76.0  3 3665.4   0.0 11.878823  1.0 11.878829

6  0.38 BL 28 658 74.0  8 3894.0 197.6 11.875175  3.0 11.875192
6  0.38 BL 28 658 76.0  8 3829.0 132.6 11.874230  1.0 11.874236
6  0.38 BL 28 658 75.0  8 3826.5 130.1 11.873981  2.0 11.873992
6  0.38 BL 28 658 76.0  8 3820.2 123.8 11.873678  1.0 11.873684
6  0.38 BL 28 658 77.0  8 3804.0 107.6 11.873033  0.0 11.873033
6  0.38 BL 28 658 77.0  8 3782.7  86.3 11.872805  0.0 11.872805
6  0.38 BL 28 658 76.0  8 3696.4   0.0 11.869981  1.0 11.869987
```

```
6  0.38 BL 90 658 74.0  4 3868.5 210.1 11.833948  3.0 11.833965
6  0.38 BL 90 658 73.0  4 3841.4 183.0 11.833591  4.0 11.833613
6  0.38 BL 90 658 74.5  4 3832.8 174.4 11.833425  2.5 11.833439
6  0.38 BL 90 658 71.5  4 3799.4 141.0 11.832605  5.5 11.832636
6  0.38 BL 90 658 78.5  4 3658.4   0.0 11.830465 -1.5 11.830457

6  0.38 BL 90 658 74.0  5 3840.8 209.9 11.874553  3.0 11.874570
6  0.38 BL 90 658 73.0  5 3813.2 182.3 11.873834  4.0 11.873856
6  0.38 BL 90 658 74.5  5 3803.5 172.6 11.873405  2.5 11.873419
6  0.38 BL 90 658 71.5  5 3771.6 140.7 11.872615  5.5 11.872646
6  0.38 BL 90 658 78.5  5 3630.9   0.0 11.870353 -1.5 11.870345

6  0.38 BL 90 658 74.0  7 3863.1 208.8 11.818466  3.0 11.818483
6  0.38 BL 90 658 73.0  7 3833.2 178.9 11.817976  4.0 11.817998
6  0.38 BL 90 658 74.5  7 3822.7 168.4 11.817484  2.5 11.817498
6  0.38 BL 90 658 71.5  7 3789.3 135.0 11.816803  5.5 11.816834
6  0.38 BL 90 658 78.5  7 3654.3   0.0 11.815085 -1.5 11.815077

7  0.45 BL 28 564 76.0  1 3814.3 222.7 11.864688  1.0 11.864694
7  0.45 BL 28 564 75.0  1 3709.5 117.9 11.861729  2.0 11.861740
7  0.45 BL 28 564 72.0  1 3693.5 101.9 11.861046  5.0 11.861074
7  0.45 BL 28 564 72.0  1 3653.0  61.4 11.861020  5.0 11.861048
7  0.45 BL 28 564 76.0  1 3591.6   0.0 11.859744  1.0 11.859750

7  0.45 BL 28 564 76.0  4 3849.6 221.6 11.834983  1.0 11.834989
7  0.45 BL 28 564 75.0  4 3748.0 120.0 11.832841  2.0 11.832852
7  0.45 BL 28 564 72.0  4 3730.5 102.5 11.832130  5.0 11.832158
7  0.45 BL 28 564 72.0  4 3687.8  59.8 11.831765  5.0 11.831793
7  0.45 BL 28 564 76.0  4 3628.0   0.0 11.830298  1.0 11.830304

7  0.45 BL 28 564 76.0  5 3877.2 227.2 11.817421  1.0 11.817427
7  0.45 BL 28 564 75.0  5 3773.0 123.0 11.816285  2.0 11.816296
7  0.45 BL 28 564 72.0  5 3756.1 106.1 11.815648  5.0 11.815676
7  0.45 BL 28 564 72.0  5 3715.2  65.2 11.815558  5.0 11.815586
7  0.45 BL 28 564 76.0  5 3650.0   0.0 11.814050  1.0 11.814056

7  0.45 BL 90 564 75.0  3 3818.9 236.6 11.788650  2.0 11.788661
7  0.45 BL 90 564 67.0  3 3769.7 187.4 11.787263 10.0 11.787319
7  0.45 BL 90 564 71.0  3 3741.2 158.9 11.786364  6.0 11.786397
7  0.45 BL 90 564 72.0  3 3721.6 139.3 11.785965  5.0 11.785993
7  0.45 BL 90 564 89.0  3 3582.3   0.0 11.785268  -12 11.785201

7  0.45 BL 90 564 75.0  6 3865.0 241.4 11.841030  2.0 11.841041
7  0.45 BL 90 564 67.0  6 3811.9 188.3 11.840323 10.0 11.840379
7  0.45 BL 90 564 71.0  6 3780.7 157.1 11.839805  6.0 11.839838
7  0.45 BL 90 564 72.0  6 3762.1 138.5 11.839429  5.0 11.839457
7  0.45 BL 90 564 89.0  6 3623.6   0.0 11.838798  -12 11.838731

7  0.45 BL 90 564 75.0  8 3841.3 231.1 11.838039  2.0 11.838050
7  0.45 BL 90 564 67.0  8 3802.6 192.4 11.837365 10.0 11.837421
7  0.45 BL 90 564 71.0  8 3773.4 163.2 11.836498  6.0 11.836531
7  0.45 BL 90 564 72.0  8 3752.9 142.7 11.836060  5.0 11.836088
7  0.45 BL 90 564 89.0  8 3610.2   0.0 11.835634  -12 11.835567
```

8	0.53	BL	28	508	76.0	1	3642.4	250.8	11.806005	1.0	11.806011
8	0.53	BL	28	508	75.0	1	3518.0	126.4	11.803656	2.0	11.803667
8	0.53	BL	28	508	72.0	1	3494.7	103.1	11.802679	5.0	11.802707
8	0.53	BL	28	508	72.0	1	3440.4	48.8	11.801963	5.0	11.801991
8	0.53	BL	28	508	76.0	1	3391.6	0.0	11.800814	1.0	11.800820
8	0.53	BL	28	508	76.0	4	3689.2	253.6	11.887953	1.0	11.887959
8	0.53	BL	28	508	75.0	4	3564.9	129.3	11.886561	2.0	11.886572
8	0.53	BL	28	508	72.0	4	3540.9	105.3	11.885460	5.0	11.885488
8	0.53	BL	28	508	72.0	4	3486.2	50.6	11.885000	5.0	11.885028
8	0.53	BL	28	508	76.0	4	3435.6	0.0	11.883750	1.0	11.883756
8	0.53	BL	28	508	76.0	5	3676.9	257.7	11.837278	1.0	11.837284
8	0.53	BL	28	508	75.0	5	3546.1	126.9	11.836061	2.0	11.836072
8	0.53	BL	28	508	72.0	5	3522.4	103.2	11.835093	5.0	11.835121
8	0.53	BL	28	508	72.0	5			11.834369	5.0	11.834397
8	0.53	BL	28	508	76.0	5	3419.2	0.0	11.833160	1.0	11.833166
8	0.53	BL	90	508	70.0	2	3710.4	264.4	11.857959	7.0	11.857998
8	0.53	BL	90	508	71.0	2	3664.2	218.2	11.857519	6.0	11.857552
8	0.53	BL	90	508	72.0	2	3642.5	196.5	11.856781	5.0	11.856809
8	0.53	BL	90	508	72.5	2	3611.5	165.5	11.856459	4.5	11.856484
8	0.53	BL	90	508	82.0	2	3446.0	0.0	11.854529	-5.0	11.854501
8	0.53	BL	90	508	70.0	3	3655.7	261.9	11.846756	7.0	11.846795
8	0.53	BL	90	508	71.0	3	3616.6	222.8	11.846666	6.0	11.846699
8	0.53	BL	90	508	72.0	3	3595.5	201.7	11.845905	5.0	11.845933
8	0.53	BL	90	508	72.5	3	3566.4	172.6	11.845621	4.5	11.845646
8	0.53	BL	90	508	82.0	3	3393.8	0.0	11.773046	-5.0	11.773018
8	0.53	BL	90	508	70.0	6	3702.5	264.1	11.776119	7.0	11.776158
8	0.53	BL	90	508	71.0	6	3652.0	213.6	11.775864	6.0	11.775897
8	0.53	BL	90	508	72.0	6	3628.6	190.2	11.775125	5.0	11.775153
8	0.53	BL	90	508	72.5	6	3600.7	162.3	11.774880	4.5	11.774905
8	0.53	BL	90	508	82.0	6	3438.4	0.0	11.773046	-5.0	11.773018
9	0.45	BL	28	658	73.0	1	3769.6	307.1	11.867524	4.0	11.867546
9	0.45	BL	28	658	74.0	1	3638.6	176.1	11.866896	3.0	11.866913
9	0.45	BL	28	658	70.5	1	3630.5	168.0	11.866040	6.5	11.866076
9	0.45	BL	28	658	71.5	1	3613.6	151.1	11.865783	5.5	11.865814
9	0.45	BL	28	658	79.0	1	3462.5	0.0	11.863079	-2.0	11.863068
9	0.45	BL	28	658	73.0	2	3754.4	302.5	11.822100	4.0	11.822122
9	0.45	BL	28	658	74.0	2	3627.2	175.3	11.821333	3.0	11.821350
9	0.45	BL	28	658	70.5	2	3618.7	166.8	11.820574	6.5	11.820610
9	0.45	BL	28	658	71.5	2	3602.5	150.6	11.820379	5.5	11.820410
9	0.45	BL	28	658	79.0	2	3451.9	0.0	11.817699	-2.0	11.817688
9	0.45	BL	28	658	73.0	6	3723.5	308.1	11.813285	4.0	11.813307
9	0.45	BL	28	658	74.0	6	3591.8	176.4	11.812489	3.0	11.812506
9	0.45	BL	28	658	70.5	6	3583.6	168.2	11.811670	6.5	11.811706
9	0.45	BL	28	658	71.5	6	3565.3	149.9	11.811471	5.5	11.811502
9	0.45	BL	28	658	79.0	6	3415.4	0.0	11.808958	-2.0	11.808947

```
 9   0.45 BL 90 658 73.0   3 3784.8 298.2 11.792576  4.0 11.792598
 9   0.45 BL 90 658 72.0   3 3750.1 263.5 11.792511  5.0 11.792539
 9   0.45 BL 90 658 74.0   3 3709.0 222.4 11.791804  3.0 11.791821
 9   0.45 BL 90 658 78.0   3 3487.2   0.6 11.788934 -1.0 11.788928
 9   0.45 BL 90 658 75.0   3 3486.6   0.0 11.788568  2.0 11.788579

 9   0.45 BL 90 658 73.0   7 3728.5 291.5 11.759663  4.0 11.759685
 9   0.45 BL 90 658 72.0   7 3702.3 265.3 11.759598  5.0 11.759626
 9   0.45 BL 90 658 74.0   7 3663.5 226.5 11.758991  3.0 11.759008
 9   0.45 BL 90 658 78.0   7 3437.2   0.2 11.756099 -1.0 11.756093
 9   0.45 BL 90 658 75.0   7 3437.0   0.0 11.755728  2.0 11.755739

 9   0.45 BL 90 658 73.0   8 3752.3 299.3 11.791845  4.0 11.791867
 9   0.45 BL 90 658 72.0   8 3714.8 261.8 11.791806  5.0 11.791834
 9   0.45 BL 90 658 74.0   8 3679.2 226.2 11.791111  3.0 11.791128
 9   0.45 BL 90 658 78.0   8 3453.4   0.4 11.788634 -1.0 11.788628
 9   0.45 BL 90 658 75.0   8 3453.0   0.0 11.788065  2.0 11.788076

10   0.33 BL 28 752 74.0   2 3797.1 251.7 11.771350  3.0 11.771367
10   0.33 BL 28 752 67.0   2 3754.4 209.0 11.770678 10.0 11.770734
10   0.33 BL 28 752 72.0   2 3600.7  55.3 11.768780  5.0 11.768808
10   0.33 BL 28 752 76.0   2 3572.7  27.3 11.768058  1.0 11.768064
10   0.33 BL 28 752 80.0   2 3545.4   0.0 11.766980 -3.0 11.766963

10   0.33 BL 28 752 74.0   5 3836.7 252.9 11.798994  3.0 11.799011
10   0.33 BL 28 752 67.0   5 3790.8 207.0 11.798210 10.0 11.798266
10   0.33 BL 28 752 72.0   5 3633.4  49.6 11.796100  5.0 11.796128
10   0.33 BL 28 752 76.0   5 3608.8  25.0 11.795620  1.0 11.795626
10   0.33 BL 28 752 80.0   5 3583.8   0.0 11.794559 -3.0 11.794542

10   0.33 BL 28 752 74.0   7 3811.2 255.7 11.746950  3.0 11.746967
10   0.33 BL 28 752 67.0   7 3763.9 208.4 11.745770 10.0 11.745826
10   0.33 BL 28 752 72.0   7 3601.8  46.3 11.743700  5.0 11.743728
10   0.33 BL 28 752 76.0   7 3579.1  23.6 11.743198  1.0 11.743204
10   0.33 BL 28 752 80.0   7 3555.5   0.0 11.742430 -3.0 11.742413

10   0.33 BL 90 752 74.0   1 3816.1 249.6 11.789759  3.0 11.789776
10   0.33 BL 90 752 69.5   1 3792.5 226.0 11.789305  7.5 11.789347
10   0.33 BL 90 752 72.0   1 3768.2 201.7 11.788834  5.0 11.788862
10   0.33 BL 90 752 70.0   1 3713.9 147.4 11.788061  7.0 11.788100
10   0.33 BL 90 752 86.0   1 3566.5   0.0 11.785028 -9.0 11.784978

10   0.33 BL 90 752 74.0   3 3819.5 260.3 11.774034  3.0 11.774051
10   0.33 BL 90 752 69.5   3 3791.7 232.5 11.773821  7.5 11.773863
10   0.33 BL 90 752 72.0   3 3767.9 208.7 11.773475  5.0 11.773503
10   0.33 BL 90 752 70.0   3 3714.3 155.1 11.772793  7.0 11.772832
10   0.33 BL 90 752 86.0   3 3559.2   0.0 11.769554 -9.0 11.769504

10   0.33 BL 90 752 74.0   6 3850.7 259.3 11.781155  3.0 11.781172
10   0.33 BL 90 752 69.5   6 3825.0 233.6 11.780923  7.5 11.780965
10   0.33 BL 90 752 72.0   6 3802.0 210.6 11.780663  5.0 11.780691
10   0.33 BL 90 752 70.0   6 3743.8 152.4 11.779895  7.0 11.779934
10   0.33 BL 90 752 86.0   6 3591.4   0.0 11.776683 -9.0 11.776633
```

```
11   0.53 BL 28 564 76.0  4 3650.3 296.7 11.781526  1.0 11.781532
11   0.53 BL 28 564 67.0  4 3445.7  92.1 11.779655 10.0 11.779711
11   0.53 BL 28 564 71.0  4 3421.8  68.2 11.778711  6.0 11.778744
11   0.53 BL 28 564 84.0  4 3353.6   0.0 11.776558 -7.0 11.776519

11   0.53 BL 28 564 76.0  6 3665.5 298.9 11.722196  1.0 11.722202
11   0.53 BL 28 564 67.0  6 3461.8  95.2 11.720778 10.0 11.720834
11   0.53 BL 28 564 71.0  6 3437.4  70.8 11.719856  6.0 11.719889
11   0.53 BL 28 564 84.0  6 3366.6   0.0 11.718626 -7.0 11.718587

11   0.53 BL 28 564 76.0  7 3677.3 299.1 11.736958  1.0 11.736964
11   0.53 BL 28 564 67.0  7 3470.7  92.5 11.735618 10.0 11.735674
11   0.53 BL 28 564 71.0  7 3447.9  69.7 11.734750  6.0 11.734783
11   0.53 BL 28 564 84.0  7 3378.2   0.0 11.733543 -7.0 11.733504

11   0.53 BL 90 564 74.0  1 3717.8 308.6 11.733791  3.0 11.733808
11   0.53 BL 90 564 69.5  1 3658.6 249.4 11.733144  7.5 11.733186
11   0.53 BL 90 564 72.0  1 3606.8 197.6 11.732605  5.0 11.732633
11   0.53 BL 90 564 70.0  1 3505.2  96.0 11.731103  7.0 11.731142
11   0.53 BL 90 564 86.0  1 3409.2   0.0 11.729701 -9.0 11.729651

11   0.53 BL 90 564 74.0  3 3716.8 308.3 11.729230  3.0 11.729247
11   0.53 BL 90 564 69.5  3 3662.3 253.8 11.728759  7.5 11.728801
11   0.53 BL 90 564 72.0  3 3609.9 201.4 11.728405  5.0 11.728433
11   0.53 BL 90 564 70.0  3 3511.1 102.6 11.726864  7.0 11.726903
11   0.53 BL 90 564 86.0  3 3408.5   0.0 11.725040 -9.0 11.724990

11   0.53 BL 90 564 74.0  8 3719.5 313.5 11.759335  3.0 11.759352
11   0.53 BL 90 564 69.5  8 3637.4 231.4 11.758381  7.5 11.758423
11   0.53 BL 90 564 72.0  8 3583.4 177.4 11.757870  5.0 11.757898
11   0.53 BL 90 564 70.0  8 3498.2  92.2 11.756548  7.0 11.756587
11   0.53 BL 90 564 86.0  8 3406.0   0.0 11.754996 -9.0 11.754946

12   0.33 BL 28 752 76.0  4 3813.0 275.1 11.767341  1.0 11.767347
12   0.33 BL 28 752 71.0  4 3656.7 118.8 11.765681  6.0 11.765714
12   0.33 BL 28 752 67.0  4 3636.9  99.0 11.764608 10.0 11.764664
12   0.33 BL 28 752 84.0  4 3537.9   0.0 11.761938 -7.0 11.761899

12   0.33 BL 28 752 76.0  7 3738.0 269.5 11.759000  1.0 11.759006
12   0.33 BL 28 752 71.0  7 3581.8 113.3 11.757363  6.0 11.757396
12   0.33 BL 28 752 67.0  7 3563.3  94.8 11.756438 10.0 11.756494
12   0.33 BL 28 752 84.0  7 3468.5   0.0 11.754293 -7.0 11.754254

12   0.33 BL 28 752 76.0  8 3791.7 268.0 11.726228  1.0 11.726234
12   0.33 BL 28 752 71.0  8 3638.2 114.5 11.724681  6.0 11.724714
12   0.33 BL 28 752 67.0  8 3620.3  96.6 11.723649 10.0 11.723705
12   0.33 BL 28 752 84.0  8 3523.7   0.0 11.721429 -7.0 11.721390

12   0.33 BL 90 752 76.0  1 3772.8 244.7 11.769775  1.0 11.769781
12   0.33 BL 90 752 75.0  1 3717.5 189.4 11.768905  2.0 11.768916
12   0.33 BL 90 752 76.5  1 3683.0 154.9 11.768546  0.5 11.768549
12   0.33 BL 90 752 76.0  1 3625.2  97.1 11.767651  1.0 11.767657
12   0.33 BL 90 752 83.0  1 3528.1   0.0 11.765868 -6.0 11.765835
```

```
12   0.33 BL 90 752 76.0  5 3815.3 254.1 11.745964  1.0 11.745970
12   0.33 BL 90 752 75.0  5 3754.2 193.0 11.745153  2.0 11.745164
12   0.33 BL 90 752 76.5  5 3717.8 156.6 11.744713  0.5 11.744716
12   0.33 BL 90 752 76.0  5 3659.4  98.2 11.743920  1.0 11.743926
12   0.33 BL 90 752 83.0  5 3561.2   0.0 11.741974 -6.0 11.741941

12   0.33 BL 90 752 76.0  6 3793.8 239.6 11.748318  1.0 11.748324
12   0.33 BL 90 752 75.0  6 3745.6 191.4 11.747934  2.0 11.747945
12   0.33 BL 90 752 76.5  6 3713.6 159.4 11.747570  0.5 11.747573
12   0.33 BL 90 752 76.0  6 3651.6  97.4 11.746665  1.0 11.746671
12   0.33 BL 90 752 83.0  6 3554.2   0.0 11.744814 -6.0 11.744781

13   0.53 RG 28 508 83.0  1 3767.4 259.0 11.695463 -6.0 11.695422
13   0.53 RG 28 508 67.0  1 3580.2  71.8 11.692345 10.0 11.692413
13   0.53 RG 28 508 66.5  1 3563.5  55.1 11.691545 10.5 11.691617
13   0.53 RG 28 508 74.5  1 3508.4   0.0 11.690765  2.5 11.690782

13   0.53 RG 28 508 83.0  3 3769.5 256.8 11.742469 -6.0 11.742428
13   0.53 RG 28 508 67.0  3 3579.1  66.4 11.739259 10.0 11.739328
13   0.53 RG 28 508 66.5  3 3563.9  51.2 11.738586 10.5 11.738658
13   0.53 RG 28 508 74.5  3 3512.7   0.0 11.737563  2.5 11.737580

13   0.53 RG 28 508 83.0  5 3774.5 256.2 11.740061 -6.0 11.740020
13   0.53 RG 28 508 67.0  5 3587.0  68.7 11.736773 10.0 11.736841
13   0.53 RG 28 508 66.5  5 3572.4  54.1 11.736026 10.5 11.736098
13   0.53 RG 28 508 74.5  5 3518.3   0.0 11.735139  2.5 11.735156

13   0.53 RG 90 508 76.0  2 3806.0 263.1 11.720879  1.0 11.720886
13   0.53 RG 90 508 75.0  2 3708.1 165.2 11.719839  2.0 11.719853
13   0.53 RG 90 508 76.5  2 3663.1 120.2 11.719579  0.5 11.719582
13   0.53 RG 90 508 76.0  2 3610.8  67.9 11.717914  1.0 11.717921
13   0.53 RG 90 508 83.0  2 3542.9   0.0 11.716850 -6.0 11.716809

13   0.53 RG 90 508 76.0  4 3798.9 262.3 11.685966  1.0 11.685973
13   0.53 RG 90 508 75.0  4 3698.6 162.0 11.684926  2.0 11.684940
13   0.53 RG 90 508 76.5  4 3654.2 117.6 11.684505  0.5 11.684508
13   0.53 RG 90 508 76.0  4 3605.1  68.5 11.683061  1.0 11.683068
13   0.53 RG 90 508 83.0  4 3536.6   0.0 11.682169 -6.0 11.682128

13   0.53 RG 90 508 76.0  6 3782.6 257.9 11.712629  1.0 11.712636
13   0.53 RG 90 508 75.0  6 3687.5 162.8 11.711590  2.0 11.711604
13   0.53 RG 90 508 76.5  6 3642.0 117.3 11.711519  0.5 11.711522
13   0.53 RG 90 508 76.0  6 3589.4  64.7 11.709988  1.0 11.709995
13   0.53 RG 90 508 83.0  6 3524.7   0.0 11.709366 -6.0 11.709325

14   0.33 RG 28 752 72.0  4 3887.6 212.4 11.632023  5.0 11.632057
14   0.33 RG 28 752 72.0  4 3805.4 130.2 11.630903  5.0 11.630937
14   0.33 RG 28 752 73.0  4 3780.7 105.5 11.630260  4.0 11.630287
14   0.33 RG 28 752 74.5  4 3750.1  74.9 11.629644  2.5 11.629661
14   0.33 RG 28 752 74.0  4 3675.2   0.0 11.626625  3.0 11.626646

14   0.33 RG 28 752 72.0  6 3990.6 210.7 11.731594  5.0 11.731628
14   0.33 RG 28 752 72.0  6 3915.5 135.6 11.730220  5.0 11.730254
14   0.33 RG 28 752 73.0  6 3889.7 109.8 11.729644  4.0 11.729671
```

```
14  0.33 RG 28 752 74.5  6 3817.6  37.7 11.728334  2.5 11.728351
14  0.33 RG 28 752 74.0  6 3779.9   0.0 11.725781  3.0 11.725802

14  0.33 RG 28 752 72.0  8 3931.6 217.0 11.689308  5.0 11.689342
14  0.33 RG 28 752 72.0  8 3848.3 133.7 11.687980  5.0 11.688014
14  0.33 RG 28 752 73.0  8 3824.1 109.5 11.687240  4.0 11.687267
14  0.33 RG 28 752 74.0  8 3714.6   0.0 11.683563  3.0 11.683584

14  0.33 RG 90 752 74.0  3 3945.5 146.7 11.725269  3.0 11.725290
14  0.33 RG 90 752 74.5  3 3865.6  66.8 11.723528  2.5 11.723545
14  0.33 RG 90 752 74.0  3 3809.6  10.8 11.723458  3.0 11.723479
14  0.33 RG 90 752 72.5  3 3798.8   0.0 11.722193  4.5 11.722224

14  0.33 RG 90 752 74.0  5 3936.4 143.3 11.719474  3.0 11.719495
14  0.33 RG 90 752 74.5  5 3855.6  62.5 11.717520  2.5 11.717537
14  0.33 RG 90 752 74.0  5 3804.0  10.9 11.717569  3.0 11.717590
14  0.33 RG 90 752 72.5  5 3793.1   0.0 11.716369  4.5 11.716400

14  0.33 RG 90 752 74.0  7 3945.3 141.8 11.708160  3.0 11.708181
14  0.33 RG 90 752 74.5  7 3868.8  65.3 11.706395  2.5 11.706412
14  0.33 RG 90 752 74.0  7 3814.0  10.5 11.706325  3.0 11.706346
14  0.33 RG 90 752 72.5  7 3803.5   0.0 11.705168  4.5 11.705199

15  0.53 RG 28 508 72.0  1 3752.3 269.1 11.666280  5.0 11.666314
15  0.53 RG 28 508 72.0  1 3595.5 112.3 11.665003  5.0 11.665037
15  0.53 RG 28 508 73.0  1 3556.1  72.9 11.663920  4.0 11.663947
15  0.53 RG 28 508 74.5  1 3490.2   7.0 11.662513  2.5 11.662530
15  0.53 RG 28 508 74.0  1 3483.2   0.0 11.661419  3.0 11.661440

15  0.53 RG 28 508 72.0  3 3725.9 262.8 11.701981  5.0 11.702015
15  0.53 RG 28 508 72.0  3 3572.7 109.6 11.700266  5.0 11.700300
15  0.53 RG 28 508 73.0  3 3534.1  71.0 11.699194  4.0 11.699221
15  0.53 RG 28 508 74.5  3 3470.7   7.6 11.698020  2.5 11.698037
15  0.53 RG 28 508 74.0  3 3463.1   0.0 11.696785  3.0 11.696806

15  0.53 RG 28 508 72.0  4 3749.6 261.1 11.737328  5.0 11.737362
15  0.53 RG 28 508 72.0  4 3600.5 112.0 11.735930  5.0 11.735964
15  0.53 RG 28 508 73.0  4 3563.7  75.2 11.734960  4.0 11.734987
15  0.53 RG 28 508 74.5  4 3497.7   9.2 11.733685  2.5 11.733702
15  0.53 RG 28 508 74.0  4 3488.5   0.0 11.732560  3.0 11.732581

15  0.53 RG 90 508 74.0  2 3725.7 237.4 11.712359  3.0 11.712380
15  0.53 RG 90 508 74.5  2 3561.6  73.3 11.710255  2.5 11.710272
15  0.53 RG 90 508 74.0  2 3499.1  10.8 11.709840  3.0 11.709861
15  0.53 RG 90 508 72.5  2 3488.3   0.0 11.709010  4.5 11.709041

15  0.53 RG 90 508 74.0  7 3730.1 245.2 11.718599  3.0 11.718620
15  0.53 RG 90 508 74.5  7 3571.3  86.4 11.716328  2.5 11.716345
15  0.53 RG 90 508 74.0  7 3511.6  26.7 11.715986  3.0 11.716007
15  0.53 RG 90 508 72.5  7 3499.1  14.2 11.715049  4.5 11.715080
15  0.53 RG 90 508 74.0  7 3484.9   0.0 11.708383  3.0 11.708404

15  0.53 RG 90 508 74.5  8 3628.2  77.6 11.746565  2.5 11.746582
15  0.53 RG 90 508 74.0  8 3564.2  13.6 11.746255  3.0 11.746276
```

15	0.53	RG	90	508	72.5	8	3550.6	0.0	11.745448	4.5	11.745479
16	0.45	RG	28	564	78.0	1	3810.4	227.5	11.712110	-1.0	11.712103
16	0.45	RG	28	564	72.5	1	3757.3	174.4	11.710628	4.5	11.710659
16	0.45	RG	28	564	72.0	1	3712.7	129.8	11.710155	5.0	11.710189
16	0.45	RG	28	564	73.5	1	3656.8	73.9	11.709435	3.5	11.709459
16	0.45	RG	28	564	82.0	1	3582.9	0.0	11.707646	-5.0	11.707612
16	0.45	RG	28	564	78.0	2	3791.5	227.2	11.685233	-1.0	11.685226
16	0.45	RG	28	564	72.5	2	3744.6	180.3	11.683865	4.5	11.683896
16	0.45	RG	28	564	72.0	2	3698.0	133.7	11.683361	5.0	11.683395
16	0.45	RG	28	564	73.5	2	3639.0	74.7	11.682658	3.5	11.682682
16	0.45	RG	28	564	82.0	2	3564.3	0.0	11.680759	-5.0	11.680725
16	0.45	RG	28	564	78.0	5	3819.1	228.6	11.672970	-1.0	11.672963
16	0.45	RG	28	564	72.5	5	3768.1	177.6	11.671736	4.5	11.671767
16	0.45	RG	28	564	72.0	5	3722.3	131.8	11.671323	5.0	11.671357
16	0.45	RG	28	564	73.5	5	3661.5	71.0	11.670610	3.5	11.670634
16	0.45	RG	28	564	82.0	5	3590.5	0.0	11.667144	-5.0	11.667110
16	0.45	RG	90	564	75.0	3	3785.2	201.4	11.710605	2.0	11.710619
16	0.45	RG	90	564	71.0	3	3741.6	157.8	11.709369	6.0	11.709410
16	0.45	RG	90	564	67.0	3	3677.7	93.9	11.708448	10.0	11.708517
16	0.45	RG	90	564	73.0	3	3604.0	20.2	11.707396	4.0	11.707423
16	0.45	RG	90	564	82.0	3	3583.8	0.0	11.707333	-5.0	11.707299
16	0.45	RG	90	564	75.0	4	3811.2	205.6	11.700979	2.0	11.700993
16	0.45	RG	90	564	71.0	4	3764.4	158.8	11.699769	6.0	11.699810
16	0.45	RG	90	564	67.0	4	3697.3	91.7	11.698841	10.0	11.698910
16	0.45	RG	90	564	73.0	4	3626.9	21.3	11.698834	4.0	11.698861
16	0.45	RG	90	564	82.0	4	3605.6	0.0	11.698105	-5.0	11.698071
16	0.45	RG	90	564	75.0	7	3833.9	203.1	11.651233	2.0	11.651247
16	0.45	RG	90	564	71.0	7	3777.7	146.9	11.649849	6.0	11.649890
16	0.45	RG	90	564	67.0	7	3719.5	88.7	11.649125	10.0	11.649193
16	0.45	RG	90	564	73.0	7	3651.9	21.1	11.648461	4.0	11.648488
16	0.45	RG	90	564	82.0	7	3630.8	0.0	11.648415	-5.0	11.648381
17	0.33	RG	28	752	78.0	1	3902.8	198.1	11.673490	-1.0	11.673483
17	0.33	RG	28	752	72.5	1	3879.9	175.2	11.672293	4.5	11.672324
17	0.33	RG	28	752	72.0	1	3848.9	144.2	11.671854	5.0	11.671888
17	0.33	RG	28	752	73.5	1	3790.0	85.3	11.671394	3.5	11.671418
17	0.33	RG	28	752	82.0	1	3704.7	0.0	11.668776	-5.0	11.668742
17	0.33	RG	28	752	78.0	2	4015.4	193.9	11.700879	-1.0	11.700872
17	0.33	RG	28	752	72.5	2	3991.1	169.6	11.699943	4.5	11.699974
17	0.33	RG	28	752	72.0	2	3963.5	142.0	11.699601	5.0	11.699635
17	0.33	RG	28	752	73.5	2	3904.7	83.2	11.699139	3.5	11.699163
17	0.33	RG	28	752	82.0	2	3821.5	0.0	11.697013	-5.0	11.696979
17	0.33	RG	28	752	78.0	3	4013.6	192.9	11.724848	-1.0	11.724841
17	0.33	RG	28	752	72.5	3	3995.0	174.3	11.723448	4.5	11.723479
17	0.33	RG	28	752	72.0	3	3966.5	145.8	11.723025	5.0	11.723059
17	0.33	RG	28	752	73.5	3	3906.4	85.7	11.722529	3.5	11.722553

17	0.33	RG	28	752	82.0	3	3820.7	0.0	11.720259	-5.0	11.720225
17	0.33	RG	90	752	75.0	5	3972.6	156.3	11.661718	2.0	11.661732
17	0.33	RG	90	752	71.0	5	3939.4	123.1	11.660273	6.0	11.660314
17	0.33	RG	90	752	67.0	5	3896.5	80.2	11.659784	10.0	11.659853
17	0.33	RG	90	752	73.0	5	3840.2	23.9	11.658941	4.0	11.658968
17	0.33	RG	90	752	82.0	5	3816.3	0.0	11.658830	-5.0	11.658796
17	0.33	RG	90	752	75.0	7	3959.4	155.0	11.722040	2.0	11.722054
17	0.33	RG	90	752	71.0	7	3927.7	123.3	11.720880	6.0	11.720921
17	0.33	RG	90	752	67.0	7	3881.4	77.0	11.720238	10.0	11.720307
17	0.33	RG	90	752	73.0	7	3828.1	23.7	11.719735	4.0	11.719762
17	0.33	RG	90	752	82.0	7	3804.4	0.0	11.719503	-5.0	11.719469
17	0.33	RG	90	752	75.0	8	3993.7	155.8	11.682914	2.0	11.682928
17	0.33	RG	90	752	71.0	8	3963.8	125.9	11.681320	6.0	11.681361
17	0.33	RG	90	752	67.0	8	3919.1	81.2	11.680864	10.0	11.680932
17	0.33	RG	90	752	73.0	8	3860.7	22.8	11.680033	4.0	11.680060
17	0.33	RG	90	752	82.0	8	3837.9	0.0	11.680094	-5.0	11.680060
18	0.45	RG	28	564	76.0	1	3778.0	221.3	11.660731	1.0	11.660738
18	0.45	RG	28	564	73.0	1	3720.2	163.5	11.659608	4.0	11.659635
18	0.45	RG	28	564	75.0	1	3688.5	131.8	11.659221	2.0	11.659235
18	0.45	RG	28	564	74.5	1	3651.1	94.4	11.658830	2.5	11.658847
18	0.45	RG	28	564	78.0	1	3556.7	0.0	11.656268	-1.0	11.656261
18	0.45	RG	28	564	76.0	2	3817.9	226.4	11.692008	1.0	11.692015
18	0.45	RG	28	564	73.0	2	3761.8	170.3	11.690969	4.0	11.690996
18	0.45	RG	28	564	75.0	2	3730.5	139.0	11.690538	2.0	11.690552
18	0.45	RG	28	564	74.5	2	3690.1	98.6	11.690280	2.5	11.690297
18	0.45	RG	28	564	78.0	2	3591.5	0.0	11.687328	-1.0	11.687321
18	0.45	RG	28	564	76.0	5	3812.2	228.4	11.674968	1.0	11.674975
18	0.45	RG	28	564	73.0	5	3751.0	167.2	11.673835	4.0	11.673862
18	0.45	RG	28	564	75.0	5	3722.3	138.5	11.673394	2.0	11.673408
18	0.45	RG	28	564	74.5	5	3683.3	99.5	11.673073	2.5	11.673090
18	0.45	RG	28	564	78.0	5	3583.8	0.0	11.670429	-1.0	11.670422
18	0.45	RG	90	564	74.0	3	3813.7	164.8	11.678944	3.0	11.678965
18	0.45	RG	90	564	70.0	3	3778.6	129.7	11.678508	7.0	11.678556
18	0.45	RG	90	564	70.0	3	3699.8	50.9	11.677951	7.0	11.677999
18	0.45	RG	90	564	72.5	3	3648.9	0.0	11.676909	4.5	11.676940
18	0.45	RG	90	564	74.0	4	3814.7	169.8	11.649665	3.0	11.649686
18	0.45	RG	90	564	70.0	4	3776.3	131.4	11.649361	7.0	11.649409
18	0.45	RG	90	564	70.0	4	3699.3	54.4	11.648856	7.0	11.648904
18	0.45	RG	90	564	72.5	4	3644.9	0.0	11.647825	4.5	11.647856
18	0.45	RG	90	564	74.0	6	3781.4	170.5	11.652153	3.0	11.652174
18	0.45	RG	90	564	70.0	6	3743.4	132.5	11.651778	7.0	11.651826
18	0.45	RG	90	564	70.0	6	3664.6	53.7	11.651194	7.0	11.651242
18	0.45	RG	90	564	72.5	6	3610.9	0.0	11.650241	4.5	11.650272
19	0.53	DL	28	508	82.0	2	3898.6	217.8	11.668398	-5.0	11.668368
19	0.53	DL	28	508	74.0	2	3829.2	148.4	11.667251	3.0	11.667269

```
19  0.53 DL 28 508 72.5  2 3776.7  95.9 11.667043  4.5 11.667070
19  0.53 DL 28 508 72.0  2 3760.8  80.0 11.666943  5.0 11.666973
19  0.53 DL 28 508 82.0  2 3680.8   0.0 11.666198 -5.0 11.666168

19  0.53 DL 28 508 82.0  5 3936.2 219.0 11.673100 -5.0 11.673070
19  0.53 DL 28 508 74.0  5 3867.0 149.8 11.672183  3.0 11.672201
19  0.53 DL 28 508 72.5  5 3814.4  97.2 11.671750  4.5 11.671777
19  0.53 DL 28 508 72.0  5 3799.3  82.1 11.671529  5.0 11.671559
19  0.53 DL 28 508 82.0  5 3717.2   0.0 11.670783 -5.0 11.670753

19  0.53 DL 28 508 82.0  6 4002.1 211.3 11.645266 -5.0 11.645236
19  0.53 DL 28 508 74.0  6 3932.8 142.0 11.644524  3.0 11.644542
19  0.53 DL 28 508 72.5  6 3882.5  91.7 11.643959  4.5 11.643986
19  0.53 DL 28 508 72.0  6 3867.6  76.8 11.643844  5.0 11.643874
19  0.53 DL 28 508 82.0  6 3790.8   0.0 11.643618 -5.0 11.643588

19  0.53 DL 90 508 74.0  1 4008.4 160.0 11.647626  3.0 11.647644
19  0.53 DL 90 508 70.0  1 3967.8 119.4 11.647566  7.0 11.647607
19  0.53 DL 90 508 70.0  1 3898.9  50.5 11.647238  7.0 11.647279
19  0.53 DL 90 508 72.5  1 3848.4   0.0 11.647005  4.5 11.647032

19  0.53 DL 90 508 74.0  3 3994.7 155.4 11.656546  3.0 11.656564
19  0.53 DL 90 508 70.0  3 3961.1 121.8 11.656536  7.0 11.656577
19  0.53 DL 90 508 70.0  3 3889.3  50.0 11.656500  7.0 11.656541
19  0.53 DL 90 508 72.5  3 3839.3   0.0 11.656061  4.5 11.656088

19  0.53 DL 90 508 74.0  8 3999.3 157.9 11.704311  3.0 11.704329
19  0.53 DL 90 508 70.0  8 3957.4 116.0 11.704211  7.0 11.704252
19  0.53 DL 90 508 70.0  8 3891.1  49.7 11.704190  7.0 11.704231
19  0.53 DL 90 508 72.5  8 3841.4   0.0 11.703826  4.5 11.703853

20  0.33 DL 28 752 77.0  3 3972.3 188.6 11.728236  0.0 11.728236
20  0.33 DL 28 752 74.0  3 3950.9 167.2 11.727403  3.0 11.727421
20  0.33 DL 28 752 73.0  3 3937.0 153.3 11.726799  4.0 11.726823
20  0.33 DL 28 752 80.0  3 3783.7   0.0 11.725694 -3.0 11.725676

20  0.33 DL 28 752 77.0  7 3946.0 228.1 11.717085  0.0 11.717085
20  0.33 DL 28 752 74.0  7 3924.2 206.3 11.716251  3.0 11.716269
20  0.33 DL 28 752 73.0  7 3909.7 191.8 11.715619  4.0 11.715643
20  0.33 DL 28 752 80.0  7 3717.9   0.0 11.713109 -3.0 11.713091

20  0.33 DL 28 752 77.0  8 3903.6 185.7 11.716115  0.0 11.716115
20  0.33 DL 28 752 74.0  8 3883.1 165.2 11.715158  3.0 11.715176
20  0.33 DL 28 752 73.0  8 3868.4 150.5 11.714394  4.0 11.714418
20  0.33 DL 28 752 80.0  8 3717.9   0.0 11.713109 -3.0 11.713091

20  0.33 DL 90 752 74.0  1 3974.5 161.6 11.715641  3.0 11.715659
20  0.33 DL 90 752 75.0  1 3913.5 100.6 11.715205  2.0 11.715217
20  0.33 DL 90 752 74.5  1 3869.4  56.5 11.715426  2.5 11.715441
20  0.33 DL 90 752 77.5  1 3861.1  48.2 11.715475 -0.5 11.715472
20  0.33 DL 90 752 80.0  1 3812.9   0.0 11.714013 -3.0 11.713995

20  0.33 DL 90 752 74.0  4 3955.1 164.3 11.712993  3.0 11.713011
20  0.33 DL 90 752 75.0  4 3896.3 105.5 11.712485  2.0 11.712497
```

```
20  0.33 DL 90 752 74.5  4 3851.0  60.2 11.712623  2.5 11.712638
20  0.33 DL 90 752 77.5  4 3841.8  51.0 11.712895 -0.5 11.712892
20  0.33 DL 90 752 80.0  4 3790.8   0.0 11.711139 -3.0 11.711121

20  0.33 DL 90 752 74.0  5 3987.0 160.9 11.689728  3.0 11.689746
20  0.33 DL 90 752 75.0  5 3930.5 104.4 11.689271  2.0 11.689283
20  0.33 DL 90 752 74.5  5 3887.2  61.1 11.689520  2.5 11.689535
20  0.33 DL 90 752 77.5  5 3877.6  51.5 11.689741 -0.5 11.689738
20  0.33 DL 90 752 80.0  5 3826.1   0.0 11.688025 -3.0 11.688007

21  0.53 DL 28 508 74.0  4 3925.6 229.8 11.659873  3.0 11.659891
21  0.53 DL 28 508 73.0  4 3881.2 185.4 11.659325  4.0 11.659349
21  0.53 DL 28 508 74.5  4 3865.8 170.0 11.659313  2.5 11.659328
21  0.53 DL 28 508 71.5  4 3824.4 128.6 11.658725  5.5 11.658758
21  0.53 DL 28 508 78.5  4 3695.8   0.0 11.657120 -1.5 11.657111

21  0.53 DL 28 508 74.0  6 3870.4 228.1 11.733969  3.0 11.733987
21  0.53 DL 28 508 73.0  6 3832.0 189.7 11.733216  4.0 11.733240
21  0.53 DL 28 508 74.5  6 3816.7 174.4 11.733260  2.5 11.733275
21  0.53 DL 28 508 71.5  6 3773.3 131.0 11.732618  5.5 11.732651
21  0.53 DL 28 508 78.5  6 3642.3   0.0 11.730984 -1.5 11.730975

21  0.53 DL 28 508 74.0  7 4059.7 228.3 11.718933  3.0 11.718951
21  0.53 DL 28 508 73.0  7 4022.8 191.4 11.718545  4.0 11.718569
21  0.53 DL 28 508 74.5  7 4006.9 175.5 11.718470  2.5 11.718485
21  0.53 DL 28 508 71.5  7 3964.3 132.9 11.717884  5.5 11.717917
21  0.53 DL 28 508 78.5  7 3831.4   0.0 11.716469 -1.5 11.716460

21  0.53 DL 90 508 80.0  1 3865.9 221.6 11.715518 -3.0 11.715500
21  0.53 DL 90 508 77.5  1 3837.7 193.4 11.714965 -0.5 11.714962
21  0.53 DL 90 508 76.5  1 3807.1 162.8 11.714378  0.5 11.714381
21  0.53 DL 90 508 77.8  1 3709.8  65.5 11.714073 -0.8 11.714069
21  0.53 DL 90 508 78.0  1 3644.3   0.0 11.712879 -1.0 11.712873

21  0.53 DL 90 508 80.0  3 3920.1 219.3 11.737404 -3.0 11.737386
21  0.53 DL 90 508 77.5  3 3892.8 192.0 11.736916 -0.5 11.736913
21  0.53 DL 90 508 76.5  3 3862.9 162.1 11.736430  0.5 11.736433
21  0.53 DL 90 508 77.8  3 3764.9  64.1 11.736165 -0.8 11.736161
21  0.53 DL 90 508 78.0  3 3700.8   0.0 11.735080 -1.0 11.735074

21  0.53 DL 90 508 80.0  8 3922.0 222.2 11.731645 -3.0 11.731627
21  0.53 DL 90 508 77.5  8 3893.8 194.0 11.731000 -0.5 11.730997
21  0.53 DL 90 508 76.5  8 3865.0 165.2 11.730583  0.5 11.730586
21  0.53 DL 90 508 77.8  8 3768.9  69.1 11.730344 -0.8 11.730340
21  0.53 DL 90 508 78.0  8 3699.8   0.0 11.729088 -1.0 11.729082

22  0.45 DL 28 564 78.0  4 3946.2 226.9 11.732960 -1.0 11.732954
22  0.45 DL 28 564 71.0  4 3899.0 179.7 11.731721  6.0 11.731756
22  0.45 DL 28 564 72.0  4 3878.0 158.7 11.731658  5.0 11.731688
22  0.45 DL 28 564 70.5  4 3828.4 109.1 11.731778  6.5 11.731816
22  0.45 DL 28 564 74.5  4 3719.3   0.0 11.728978  2.5 11.728993

22  0.45 DL 28 564 78.0  6 3991.0 226.4 11.703264 -1.0 11.703258
22  0.45 DL 28 564 71.0  6 3943.3 178.7 11.702165  6.0 11.702200
```

```
22  0.45 DL 28 564 72.0  6 3921.5 156.9 11.701986  5.0 11.702016
22  0.45 DL 28 564 70.5  6 3872.5 107.9 11.702108  6.5 11.702146
22  0.45 DL 28 564 74.5  6 3764.6   0.0 11.699490  2.5 11.699505

22  0.45 DL 28 564 78.0  7 3914.8 223.3 11.724630 -1.0 11.724624
22  0.45 DL 28 564 71.0  7 3867.3 175.8 11.723565  6.0 11.723600
22  0.45 DL 28 564 72.0  7 3848.6 157.1 11.723335  5.0 11.723365
22  0.45 DL 28 564 70.5  7 3789.3  97.8 11.723405  6.5 11.723443
22  0.45 DL 28 564 74.5  7 3691.5   0.0 11.720719  2.5 11.720734

22  0.45 DL 90 564 80.0  2 3942.3 207.5 11.734014 -3.0 11.733996
22  0.45 DL 90 564 77.5  2 3918.2 183.4 11.733419 -0.5 11.733416
22  0.45 DL 90 564 76.5  2 3892.9 158.1 11.731725  0.5 11.731728
22  0.45 DL 90 564 77.8  2 3804.7  69.9 11.732659 -0.8 11.732655
22  0.45 DL 90 564 78.0  2 3734.8   0.0 11.731501 -1.0 11.731495

22  0.45 DL 90 564 80.0  3 4054.1 202.9 11.690328 -3.0 11.690310
22  0.45 DL 90 564 77.5  3 4030.4 179.2 11.689819 -0.5 11.689816
22  0.45 DL 90 564 76.5  3 4007.1 155.9 11.689096  0.5 11.689099
22  0.45 DL 90 564 77.8  3 3924.0  72.8 11.689145 -0.8 11.689141
22  0.45 DL 90 564 78.0  3 3851.2   0.0 11.687825 -1.0 11.687819

22  0.45 DL 90 564 80.0  5 4020.5 202.9 11.730130 -3.0 11.730112
22  0.45 DL 90 564 77.5  5 3998.6 181.0 11.728930 -0.5 11.728927
22  0.45 DL 90 564 76.5  5 3975.3 157.7 11.728374  0.5 11.728377
22  0.45 DL 90 564 77.8  5 3892.1  74.5 11.728548 -0.8 11.728544
22  0.45 DL 90 564 78.0  5 3817.6   0.0 11.727185 -1.0 11.727179

23  0.33 DL 28 752 75.0  1 3974.4 158.9 11.719911  2.0 11.719923
23  0.33 DL 28 752 67.0  1 3953.1 137.6 11.719093 10.0 11.719152
23  0.33 DL 28 752 71.0  1 3942.4 126.9 11.718530  6.0 11.718565
23  0.33 DL 28 752 72.0  1 3933.7 118.2 11.718400  5.0 11.718430
23  0.33 DL 28 752 89.0  1 3815.5   0.0 11.718095  -12 11.718024

23  0.33 DL 28 752 75.0  5 3942.9 158.8 11.748233  2.0 11.748245
23  0.33 DL 28 752 67.0  5 3921.3 137.2 11.747003 10.0 11.747062
23  0.33 DL 28 752 71.0  5 3910.7 126.6 11.746254  6.0 11.746289
23  0.33 DL 28 752 72.0  5 3902.4 118.3 11.746108  5.0 11.746138
23  0.33 DL 28 752 89.0  5 3784.1   0.0 11.745933  -12 11.745862

23  0.33 DL 28 752 75.0  6 3925.0 157.6 11.771068  2.0 11.771080
23  0.33 DL 28 752 67.0  6 3907.3 139.9 11.770216 10.0 11.770275
23  0.33 DL 28 752 71.0  6 3896.1 128.7 11.769678  6.0 11.769713
23  0.33 DL 28 752 72.0  6 3887.5 120.1 11.769444  5.0 11.769474
23  0.33 DL 28 752 89.0  6 3767.4   0.0 11.769393  -12 11.769322

23  0.33 DL 90 752 82.0  2 3969.4 139.8 11.764124 -5.0 11.764094
23  0.33 DL 90 752 73.8  2 3936.0 106.4 11.763485  3.3 11.763504
23  0.33 DL 90 752 80.0  2 3918.0  88.4 11.763264 -3.0 11.763246
23  0.33 DL 90 752 78.5  2 3906.1  76.5 11.763184 -1.5 11.763175
23  0.33 DL 90 752 78.0  2 3829.6   0.0 11.763168 -1.0 11.763162

23  0.33 DL 90 752 82.0  3 3965.1 136.8 11.747821 -5.0 11.747791
23  0.33 DL 90 752 73.8  3 3929.5 101.2 11.747274  3.3 11.747293
```

```
23   0.33 DL 90 752 80.0  3 3912.4  84.1 11.747073 -3.0 11.747055
23   0.33 DL 90 752 78.5  3 3902.2  73.9 11.747025 -1.5 11.747016
23   0.33 DL 90 752 78.0  3 3828.3   0.0 11.746078 -1.0 11.746072

23   0.33 DL 90 752 82.0  7 3953.3 136.5 11.746870 -5.0 11.746840
23   0.33 DL 90 752 73.8  7 3915.6  98.8 11.746516  3.3 11.746535
23   0.33 DL 90 752 80.0  7 3899.9  83.1 11.746269 -3.0 11.746251
23   0.33 DL 90 752 78.5  7 3890.1  73.3 11.746195 -1.5 11.746186
23   0.33 DL 90 752 78.0  7 3816.8   0.0 11.744158 -1.0 11.744152

24   0.45 DL 28 564 70.0  4 3850.8 221.0 11.725441  7.0 11.725482
24   0.45 DL 28 564 71.0  4 3815.7 185.9 11.725394  6.0 11.725429
24   0.45 DL 28 564 72.0  4 3802.2 172.4 11.724690  5.0 11.724720
24   0.45 DL 28 564 72.5  4 3784.0 154.2 11.724573  4.5 11.724600
24   0.45 DL 28 564 82.0  4 3629.8   0.0 11.723201 -5.0 11.723171

24   0.45 DL 28 564 70.0  5 3914.2 220.5 11.752840  7.0 11.752881
24   0.45 DL 28 564 71.0  5 3887.6 193.9 11.752805  6.0 11.752840
24   0.45 DL 28 564 72.0  5 3875.0 181.3 11.752329  5.0 11.752359
24   0.45 DL 28 564 72.5  5 3856.1 162.4 11.752139  4.5 11.752166
24   0.45 DL 28 564 82.0  5 3693.7   0.0 11.750796 -5.0 11.750766

24   0.45 DL 28 564 70.0  6 3843.1 218.3 11.729280  7.0 11.729321
24   0.45 DL 28 564 71.0  6 3811.3 186.5 11.729224  6.0 11.729259
24   0.45 DL 28 564 72.0  6 3797.6 172.8 11.728708  5.0 11.728738
24   0.45 DL 28 564 72.5  6 3779.4 154.6 11.728536  4.5 11.728563
24   0.45 DL 28 564 82.0  6 3624.8   0.0 11.727156 -5.0 11.727126

24   0.45 DL 90 564 82.0  1 3912.9 198.5 11.741986 -5.0 11.741956
24   0.45 DL 90 564 73.8  1 3847.4 133.0 11.740646  3.3 11.740665
24   0.45 DL 90 564 80.0  1 3814.2  99.8 11.740915 -3.0 11.740897
24   0.45 DL 90 564 78.5  1 3797.3  82.9 11.740890 -1.5 11.740881
24   0.45 DL 90 564 78.0  1 3714.4   0.0 11.739303 -1.0 11.739297

24   0.45 DL 90 564 82.0  7 3888.9 205.8 11.721024 -5.0 11.720994
24   0.45 DL 90 564 73.8  7 3818.4 135.3 11.719414  3.3 11.719433
24   0.45 DL 90 564 80.0  7 3785.2 102.1 11.719770 -3.0 11.719752
24   0.45 DL 90 564 78.5  7 3768.0  84.9 11.719729 -1.5 11.719720
24   0.45 DL 90 564 78.0  7 3683.1   0.0 11.717873 -1.0 11.717867

24   0.45 DL 90 564 82.0  8 3893.7 207.3 11.731008 -5.0 11.730978
24   0.45 DL 90 564 73.8  8 3822.8 136.4 11.729528  3.3 11.729547
24   0.45 DL 90 564 80.0  8 3789.5 103.1 11.729995 -3.0 11.729977
24   0.45 DL 90 564 78.5  8 3771.9  85.5 11.729869 -1.5 11.729860
24   0.45 DL 90 564 78.0  8 3686.4   0.0 11.728006 -1.0 11.728000
```

APPENDIX F

LENGTH READINGS OF WATER-SATURATED IN-SERVICE CONCRETE SPECIMENS

COEFFICIENT OF THERMAL EXPANSION
SATURATED SAMPLES
FIELD SPECIMENS

LEGEND

COLUMN A = SITE NUMBER
COLUMN B = SPECIMEN IDENTIFICATION NUMBER (SEPARATED BY DASHES)
COLUMN C = SPECIMEN TEMPERATURE (DEG. F)
COLUMN D = LENGTH OF FIRST SPECIMEN IN COL. B (IN.)
COLUMN E = LENGTH OF SECOND SPECIMEN IN COL. B (IN.)
COLUMN F = LENGTH OF THIRD SPECIMEN IN COL. B (IN.)

A	B	C	D	E	F
1	21-22-23	84.0	9.552694	9.554261	9.516990
1		107.0	9.554779	9.556520	9.519005
1		122.0	9.554580	9.556279	9.518028
1		139.0	9.556058	9.557766	9.519818
2	31-52-53	84.0	9.686300	9.471179	9.674980
2		107.0	9.689018	9.473544	9.677635
2		122.0	9.689428	9.473715	9.677754
2		139.0	9.691713	9.475745	9.680076
3	52-53	79.0	9.334530	9.391128	
3		104.0	9.336091	9.392643	
3		120.0	9.336929	9.393425	
3		138.0	9.338361	9.394650	
4	13-53	84.0	9.533498	9.533993	
4		107.0	9.535243	9.535314	
4		122.0	9.534900	9.534808	
4		139.0	9.536055	9.535708	
4	11-12-51	79.0	9.429314	9.342338	9.283049
4		104.0	9.430603	9.343743	9.284413
4		120.0	9.431199	9.344254	9.285020
4		138.0	9.433654	9.345804	9.287013
5	31-32-33	80.0	9.554698	9.611925	9.626213
5		106.0	9.556045	9.613469	9.628316
5		123.0	9.556966	9.614412	9.628478
5		139.0	9.557856	9.615733	9.629395
5	SH5	79.0	9.421560		
5		104.0	9.423107		
5		120.0	9.423983		
5		138.0	9.425607		
6	43-51-53	80.0	9.502685	9.565470	9.600287
6		106.0	9.604945	9.567116	9.601632
6		123.0	9.605391	9.567978	9.602240
6		139.0	9.606135	9.569737	9.603272

7	21-22-23	80.0	9.494173	9.554134	9.525475
7		106.0	9.495514	9.555665	9.527160
7		123.0	9.496506	9.556754	9.528180
7		139.0	9.498065	9.558015	9.528998
8	9-11	79.0	9.434914	9.396571	
8		104.0	9.437069	9.398443	
8		120.0	9.438028	9.399689	
8		138.0	9.440596	9.402151	
9	43	79.0	9.407190		
9		104.0	9.408730		
9		120.0	9.409470		
9		138.0	9.410670		

APPENDIX G

LENGTH READINGS OF OVEN-DRIED IN-SERVICE CONCRETE SPECIMENS

COEFFICIENT OF THERMAL EXPANSION
DRY SAMPLES
FIELD SPECIMENS

LEGEND

COLUMN A = SITE NUMBER
COLUMN B = SPECIMEN NUMBERS
COLUMN C = SPECIMEN TEMPERATURE (DEG. F)
COLUMN D = LENGTH OF FIRST SPECIMEN IN COL. B (IN.)
COLUMN E = LENGTH OF SECOND SPECIMEN IN COL. B (IN.)
COLUMN F = LENGTH OF THIRD SPECIMEN IN COL. B (IN.)
COLUMN G = LENGTH OF FOURTH SPECIMEN IN COL. B (IN.)

A	B	C	D	E	F	G
1	21-22-23	80.0	9.551104	9.552618	9.517154	
1		106.5	9.552984	9.554539	9.518395	
1		123.5	9.553186	9.554923	9.518664	
1		145.0	9.554269	9.555875	9.518996	
2	31-52-53	74.0	9.684249	9.469818	9.673293	
2		96.0	9.685373	9.470863	9.674444	
2		126.5	9.688038	9.473246	9.676885	
2		142.5	9.689125	9.474099	9.677931	
3	52-53	84.0	9.332578	9.389929		
3		103.0	9.332667	9.390823		
3		122.0	9.334393	9.391579		
3		138.0	9.335208	9.392208		
4	13-53	79.0	9.531903	9.532036		
4		104.0	9.533026	9.533129		
4		126.0	9.533973	9.534403		
4		141.5	9.534095	9.534613		
4	11-12-51-52	84.0	9.428029	9.340398	9.281261	9.261411
4		103.0	9.429191	9.341395	9.282359	9.262270
4		122.0	9.429669	9.341906	9.282880	9.262864
4		138.0	9.429790	9.342521	9.283261	9.263119
5	31-32-33	77.0	9.553380	9.610879	9.626198	
5		110.5	9.554659	9.612161	9.627535	
5		120.5	9.555101	9.612574	9.627884	
5		140.0	9.556558	9.614263	9.629476	
5	SH5	84.0	9.420355			
5		103.0	9.421439			
5		122.0	9.422215			
5		138.0	9.422963			
6	43-51-53	82.0	9.602021	9.564619	9.599749	
6		107.0	9.602609	9.565470	9.600433	
6		123.0	9.603383	9.566131	9.601028	
6		143.0	9.604075	9.566639	9.601491	

7	21-22-23	82.0	9.493468	9.553110	9.524770	
7		107.0	9.494351	9.554045	9.525769	
7		123.0	9.495185	9.554909	9.526655	
7		143.0	9.495923	9.555703	9.527501	
8	9-11	84.0	9.431625	9.392004		
8		103.0	9.433164	9.393079		
8		122.0	9.433796	9.394001		
8		138.0	9.434688	9.394886		
9	43	84.0	9.406314			
9		103.0	9.407454			
9		122.0	9.408190			
9		138.0	9.408898			
10	5-4	82.4	9.65313	9.55861		
10		104.0	9.65405	9.55949		
10		122.0	9.65478	9.56018		
10		132.8	9.65534	9.56085		
10	13-6-3-8	86.0	9.58296	9.65165	9.59927	9.63315
10		104.0	9.58316	9.64192	9.59947	9.63314
10		122.0	9.58363	9.64235	9.59998	9.63313
10		140.0	9.58424	9.64306	9.60076	9.63385
10	10-9-12-14	86.0	9.65378	9.74322	9.61933	9.65369
10		104.0	9.65391	9.74453	9.61973	9.65449
10		122.0	9.65425	9.74515	9.62066	9.65511
10		140.0	9.65476	9.74600	9.62134	9.65568
10	11-7-2-1	87.1	9.56058	9.50082	9.54600	9.58448
10		103.1	9.56096	9.50124	9.54643	9.58474
10		126.5	9.56230	9.50213	9.54776	9.58589
10		139.1	9.56277	9.50242	9.54833	9.58629
10	15	87.1	9.63825			
10		103.1	9.63843			
10		126.5	9.63996			
10		139.1	9.64049			
11	1-12-4-10	82.4	9.58942	9.69154	9.50894	9.64736
11		104.0	9.59046	9.69247	9.50990	9.64824
11		122.0	9.59094	9.69311	9.51054	9.64883
11		132.8	9.59131	9.69364	9.51101	9.64922
11	5-7-9-3	82.4	9.54732	9.58427	9.59401	9.52540
11		104.0	9.54824	9.58526	9.59490	9.52643
11		122.0	9.54886	9.58538	9.60535	9.52704
11		132.8	9.54930	9.58590	9.59603	9.52728
11	8-11	82.4	9.55999	9.59973		
11		104.0	9.56102	9.60078		
11		122.0	9.56162	9.60171		
11		132.8	9.56211	9.60216		

11	14-15-6-13	86.0	9.60219	9.75825	9.74377	9.75764
11		104.0	9.60234	9.75849	9.74411	9.75785
11		122.0	9.60299	9.75902	9.74458	9.75854
11		140.0	9.60319	9.75933	9.74479	9.75890
11	2	87.1	9.58107			
11		103.1	9.58125			
11		126.5	9.58241			
11		139.1	9.58285			

APPENDIX H

LENGTH READINGS OF PARTIALLY-SATURATED IN-SERVICE CONCRETE SPECIMENS

COEFFICIENT OF MOISTURE EXPANSION
PARTIALLY-DRY SAMPLES
FIELD SPECIMENS

LEGEND

COLUMN A = SITE / SLAB / CORE NUMBER
COLUMN B = AMBIENT TEMPERATURE
COLUMN C = WEIGHT OF CONCRETE SPECIMEN
COLUMN D = MEASURED LENGTH OF SPECIMEN
COLUMN E = CHANGE IN TEMP. FROM REF. TEMP. OF 77°F
COLUMN F = LENGTH OF SPECIMEN CORRECTED FOR TEMP.
COLUMN G = CHANGE IN WEIGHT WITH RESPECT TO OVEN-DRIED WEIGHT
COLUMN H = CHANGE IN CORRECTED LENGTH RESPECT TO OVEN-DRIED CORRECTED LENGTH

A	B	C	D	E	F	G	H
1/2/1	84.0	2803.7	9.552694	-7.0	9.552656	162.0	0.00157
	76.0	2743.3	9.552665	1.0	9.552670	101.6	0.00158
	79.0	2720.1	9.552428	-2.0	9.552416	78.4	0.00133
	83.0	2702.2	9.551968	-6.0	9.551935	60.5	0.00085
	80.0	2641.7	9.551104	-3.0	9.551087	0.0	0.00000
1/2/2	84.0	2513.7	9.554261	-7.0	9.554224	145.3	0.00162
	76.0	2455.7	9.554364	1.0	9.554369	87.3	0.00177
	79.0	2436.0	9.554156	-2.0	9.554145	67.6	0.00154
	83.0	2421.3	9.553674	-6.0	9.553641	52.9	0.00104
	80.0	2368.4	9.552618	-3.0	9.552601	0.0	0.00000
1/2/3	84.0	2992.2	9.516990	-7.0	9.516952	162.6	-0.00019
	76.0	2929.3	9.516551	1.0	9.516556	99.7	-0.00058
	79.0	2907.3	9.516208	-2.0	9.516196	77.7	-0.00094
	83.0	2891.4	9.516019	-6.0	9.515986	61.8	-0.00115
	80.0	2829.6	9.517154	-3.0	9.517137	0.0	0.00000
2/3/1	84.0	3118.3	9.686300	-7.0	9.686243	124.3	0.00197
	76.0	3055.2	9.686483	1.0	9.686490	61.2	0.00222
	79.0	3035.2	9.686306	-2.0	9.686290	41.2	0.00202
	83.0	3018.6	9.686235	-6.0	9.686186	24.6	0.00191
	74.0	2994.0	9.684249	3.0	9.684273	0.0	0.00000
2/5/2	84.0	2991.2	9.471179	-7.0	9.471122	103.3	0.00128
	76.0	2939.3	9.471300	1.0	9.471308	51.4	0.00147
	79.0	2921.9	9.471064	-2.0	9.471047	34.0	0.00121
	83.0	2906.5	9.470889	-6.0	9.470840	18.6	0.00100
	74.0	2887.9	9.469818	3.0	9.469841	0.0	0.00000
2/5/3	84.0	3091.5	9.674980	-7.0	9.674923	106.7	0.00161
	76.0	3037.8	9.675509	1.0	9.675516	53.0	0.00220
	79.0	3019.9	9.675310	-2.0	9.675293	35.1	0.00198
	83.0	3003.5	9.675196	-6.0	9.675147	18.7	0.00183

	74.0	2984.8	9.673293	3.0	9.673316	0.0	0.00000
3/5/2	79.0	2915.8	9.334530	-2.0	9.334518	155.1	0.00198
	80.5	2844.3	9.335380	-3.5	9.335359	83.6	0.00282
	84.5	2815.0	9.334863	-7.5	9.334818	54.3	0.00228
	84.0	2758.8	9.335838	-7.0	9.335796	-1.9	0.00326
	84.0	2760.7	9.332578	-7.0	9.332536	0.0	0.00000
3/5/3	79.0	2853.7	9.391128	-2.0	9.391115	164.3	0.00123
	80.5	2773.7	9.391645	-3.5	9.391624	84.3	0.00174
	84.5	2739.0	9.391009	-7.5	9.390965	49.6	0.00108
	84.0	2681.5	9.389398	-7.0	9.389356	-7.9	-0.00053
	84.0	2689.4	9.389929	-7.0	9.389888	0.0	0.00000
4/1/3	84.0	2860.7	9.533498	-7.0	9.533463	166.9	0.00157
	76.0	2804.3	9.532826	1.0	9.532831	110.5	0.00094
	79.0	2783.7	9.532851	-2.0	9.532841	89.9	0.00095
	83.0	2767.9	9.532423	-6.0	9.532393	74.1	0.00050
	79.0	2693.8	9.531903	-2.0	9.531892	0.0	0.00000
4/5/3	84.0	2983.8	9.533993	-7.0	9.533958	172.0	0.00193
	76.0	2920.9	9.532143	1.0	9.532147	109.1	0.00012
	79.0	2901.0	9.531789	-2.0	9.531779	89.2	-0.00025
	83.0	2884.9	9.531284	-6.0	9.531255	73.1	-0.00077
	79.0	2811.8	9.532036	-2.0	9.532026	0.0	0.00000
4/1/1	79.0	3210.1	9.429314	-2.0	9.429304	149.2	0.00131
	80.5	3142.5	9.428966	-3.5	9.428949	81.6	0.00095
	84.5	3117.4	9.429581	-7.5	9.429545	56.5	0.00155
	84.0	3052.3	9.428865	-7.0	9.428831	-8.6	0.00084
	84.0	3060.9	9.428029	-7.0	9.427995	0.0	0.00000
4/1/2	79.0	2764.1	9.342338	-2.0	9.342327	130.8	0.00196
	80.5	2707.5	9.341851	-3.5	9.341834	74.2	0.00147
	84.5	2683.0	9.341374	-7.5	9.341337	49.7	0.00097
	84.0	2628.1	9.339814	-7.0	9.339780	-5.2	-0.00058
	84.0	2633.3	9.340398	-7.0	9.340363	0.0	0.00000
4/5/1	79.0	2920.5	9.283049	-2.0	9.283039	138.4	0.00181
	80.5	2859.4	9.283224	-3.5	9.283207	77.3	0.00198
	84.5	2836.4	9.283030	-7.5	9.282994	54.3	0.00177
	84.0	2774.2	9.282588	-7.0	9.282553	-7.9	0.00133
	84.0	2782.1	9.281261	-7.0	9.281227	0.0	0.00000
4/5/2	79.0	2910.2	9.262780	-2.0	9.262770	130.7	0.00139
	80.5	2856.7	9.262695	-3.5	9.262678	77.2	0.00130
	84.5	2834.8	9.263069	-7.5	9.263032	55.3	0.00166
	84.0	2770.7	9.263990	-7.0	9.263956	-8.8	0.00258
	84.0	2779.5	9.261411	-7.0	9.261377	0.0	0.00000
5/3/1	80.0	3064.1	9.554698	-3.0	9.554680	156.8	0.00130
	79.0	3029.7	9.554699	-2.0	9.554687	122.4	0.00131
	79.5	3004.2	9.554721	-2.5	9.554707	96.9	0.00133
	85.0	2975.8	9.554485	-8.0	9.554440	68.5	0.00106

	77.0	2907.3	9.553380	0.0	9.55338	0.0	0.00000
5/3/2	80.0	3070.2	9.611925	-3.0	9.611908	161.3	0.00103
	79.0	3037.8	9.612054	-2.0	9.612042	128.9	0.00116
	79.5	3012.8	9.612030	-2.5	9.612016	103.9	0.00114
	85.0	2982.1	9.612158	-8.0	9.612113	73.2	0.00123
	77.0	2908.9	9.610879	0.0	9.610878	0.0	0.00000
5/3/3	80.0	3013.3	9.626213	-3.0	9.626195	156.4	-0.00000
	79.0	2975.8	9.626205	-2.0	9.626193	118.9	-0.00000
	79.5	2947.9	9.626228	-2.5	9.626213	91.0	0.00002
	85.0	2920.6	9.626036	-8.0	9.625992	63.7	-0.00021
	77.0	2856.9	9.626198	0.0	9.626197	0.0	0.00000
5/S5	79.0	2935.8	9.421560	-2.0	9.421547	138.6	0.00124
	80.5	2886.8	9.422191	-3.5	9.422169	89.6	0.00186
	84.5	2857.3	9.422285	-7.5	9.422239	60.1	0.00193
	84.0	2806.0	9.425705	-7.0	9.425662	8.8	0.00535
	84.0	2797.2	9.420355	-7.0	9.420312	0.0	0.00000
6/4/3	80.0	3034.8	9.602685	-3.0	9.602671	185.0	0.00067
	79.0	2978.3	9.603316	-2.0	9.603307	128.5	0.00131
	79.5	2952.4	9.603261	-2.5	9.603250	102.6	0.00125
	85.0	2925.1	9.602669	-8.0	9.602632	75.3	0.00063
	82.0	2849.8	9.602021	-5.0	9.601998	0.0	0.00000
6/5/1	80.0	2988.3	9.565470	-3.0	9.565456	166.9	0.00086
	79.0	2933.7	9.566319	-2.0	9.566309	112.3	0.00171
	79.5	2909.5	9.566156	-2.5	9.566145	88.1	0.00155
	85.0	2888.0	9.565505	-8.0	9.565468	66.6	0.00087
	82.0	2821.4	9.564619	-5.0	9.564596	0.0	0.00000
6/5/3	80.0	2907.8	9.600288	-3.0	9.600273	170.7	0.00055
	79.0	2859.2	9.600491	-2.0	9.600482	122.1	0.00076
	79.5	2833.2	9.600351	-2.5	9.600340	96.1	0.00061
	85.0	2811.2	9.600304	-8.0	9.600267	74.1	0.00054
	82.0	2737.1	9.599749	-5.0	9.599726	0.0	0.00000
7/2/1	80.0	3008.1	9.494173	-3.0	9.494155	252.4	0.00072
	79.0	2897.2	9.493805	-2.0	9.493793	141.5	0.00035
	79.5	2848.3	9.493700	-2.5	9.493686	92.6	0.00025
	85.0	2810.5	9.493288	-8.0	9.493242	54.8	-0.00020
	82.0	2755.7	9.493468	-5.0	9.493439	0.0	0.00000
7/2/2	80.0	3054.5	9.554134	-3.0	9.554117	259.2	0.00103
	79.0	2938.4	9.554305	-2.0	9.554293	143.1	0.00121
	79.5	2886.9	9.554184	-2.5	9.554169	91.6	0.00109
	85.0	2848.9	9.553643	-8.0	9.553597	53.6	0.00052
	82.0	2795.3	9.553110	-5.0	9.553082	0.0	0.00000
7/2/3	80.0	2748.7	9.525475	-3.0	9.525458	215.9	0.00072
	79.0	2648.6	9.525568	-2.0	9.525556	115.8	0.00081
	79.5	2609.0	9.525538	-2.5	9.525523	76.2	0.00078
	85.0	2579.5	9.525051	-8.0	9.525006	46.7	0.00026

	82.0	2532.8	9.524770	-5.0	9.524742	0.0	0.00000
8/ /9	79.0	3129.6	9.434914	-2.0	9.434898	304.6	0.00333
	80.5	2933.9	9.435543	-3.5	9.435515	108.9	0.00394
	84.5	2871.2	9.434570	-7.5	9.434511	46.2	0.00294
	84.0	2814.9	9.431735	-7.0	9.431680	-10.1	0.00011
	84.0	2825.0	9.431625	-7.0	9.431570	0.0	0.00000
8//11	79.0	3008.8	9.396571	-2.0	9.396555	261.6	0.00461
	80.5	2820.0	9.396923	-3.5	9.396895	72.8	0.00495
	84.5	2762.0	9.396343	-7.5	9.396284	14.8	0.00433
	84.0	2699.7	9.393840	-7.0	9.393785	-47.5	0.00184
	84.0	2747.2	9.392004	-7.0	9.391949	0.0	0.00000
9/4/3	79.0	2672.6	9.407188	-2.0	9.407176	257.0	0.00090
	80.5	2489.6	9.406376	-3.5	9.406356	74.0	0.00008
	84.5	2439.9	9.405683	-7.5	9.405640	24.3	-0.00063
	84.0	2404.6	9.403995	-7.0	9.403955	-11.0	-0.00232
	84.0	2415.6	9.406314	-7.0	9.406274	0.0	0.00000

REFERENCES

1. American Concrete Institute. Temperature and Concrete, SP-25. Detroit, Michigan: American Concrete Institute, 1971.

2. Browne, R. D. "Thermal Movement of Concrete." Concrete. The Journal of the Concrete Society (London), Vol. 6, No. 10 (October, 1972), pp. 51-53.

3. Mitchell, L. J. "Hardened Concrete: Thermal Properties." In Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM Special Technical Publication No. 169-A. Philadelphia, PA: American Society for Testing and Materials, 1966, pp. 202-210.

4. Neville, A. M. Properties of Concrete. 3rd ed. Essex, England: Longman Scientific and Technical, 1987; New York: John Wiley & Sons, Inc., 1987.

5. Dettling, Heinz. "The Thermal Expansion of Hardened Cement Paste, Aggregates, and Concrete." Bulletin No. 164, Berlin, 1964. Available from SLA Translation Center, John Crerar Library, Chicago.

6. Portland Cement Association. Design and Control of Concrete Mixtures. 12th ed. Skokie, Illinois: Portland Cement Association 1979.

7. Powers, T. C. and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste," Part 9, Proceedings of American Concrete Institute, Vol. 43 (April 1947), pp. 971-992.

8. Meyers, S. L. "Thermal Expansion Characteristics of Hardened Cement Paste and of Concrete." Proceedings of Highway Research Board, Vol. 30 (1950), pp. 193-203.

9. Fintel, Mark, ed. Handbook of Concrete Engineering. 2nd ed. New York: Van Nostrand Reinhold Company, 1975.

10. Berwanger, Carl and A. Faruque Sarkar. "Thermal Expansion of Concrete and Reinforced Concrete." ACI Journal, Title No. 73-52 (November, 1976), pp. 618-621.

11. Goldbeck, A. T. and F. H. Jackson. "Tne Expansion and Contraction of Concrete and Concrete Roads." U.S. Dept. of Agriculture, Bulletin No. 532, October 13, 1917, pp. 1-31.

12. Matsumoto, Torata. "A Study of the Effect of Moisture Content Upon the Expansion and Contraction of Plain and Reinforced Concrete." University of Illinois Engineering Experiment Station, Bulletin No. 126 (Dec. 5, 1921), pp. 1-29.

13. Pence, W. D. "Thermal Coefficient of Expansion of Concrete." Journal of the Western Society of Engineers, Vol. 6 (Nov. and Dec., 1901), pp. 549-575.

14. Saemann, J. C. and G. W. Washa. "Variation of Mortar and Concrete Properties with Temperature." Journal of the American Concrete Institute, Title No. 54-20 (Nov., 1857), pp. 385-395.

15. Cruz, C. R. and M. Gillen. "Thermal Expansion of Portland Cement Paste, Mortar, and Concrete at High Temperatures." (RD074.01T) Portland Cement Association. 1981.

16. Willis, T. F. and M. E. De Reus. "Thermal Volume Change and Elasticity of Aggregates and Their Effect on Concrete." Proceedings of the American Society for Testing Materials, Vol. 39 (1939), pp. 919-928.

17. Mitchell, Leonard J. "Thermal Expansion Tests on Aggregates, Neat Cements, and Concretes." Proceedings of the American Society for Testing Materials, Vol. 53 (1953), pp. 963-977.

18. Parsons, Willard and Walter H. Johnson. "Factors Affecting the Thermal Expansion of Concrete Aggregate Materials." Journal of the American Concrete Institute, Vol. 15, No. 5 (April, 1944), ACI Proceedings Vol. 40, pp. 457-466.

19. Bonnell, D.G.R. and F. C. Harper. "The Thermal Expansion of Concrete." Journal of the Institution of Civil Engineers, Vol. 33, No. 4 (February 1950), pp. 320-330.

20. Bonnell, D.G.R. and A. Watson. "An Apparatus for Measuring Small Changes in Linear Dimensions." Journal of Scientific Instruments, Vol. 37, No. 1 (January 1950), pp. 10-12.

21. American Concrete Institute. ACI Manual of Concrete Practice, Part 1. Detroit, Michigan: American Concrete Institute, 1985, pp. 209R-24 to 209R-25.

22. Davis, Raymond E. "A Summary of Investigations of Volume Changes in Cements, Mortars and Concretes Produced by Causes Other Than Stress." Proceedings of the American Society for Testing Materials, Vol. 30, Part 1 (1930), pp. 668-685.

23. Emanuel, Jack H. and J. Leroy Hulsey. "Prediction of the Thermal Coefficient of Expansion of Concrete." *ACI Journal*, Title No. 74-14 (April, 1977), pp. 149-155.

24. Neville, Adam M. *Hardened Concrete: Physical and Mechanical Aspects*. Detroit, Michigan: American Concrete Institute; Ames, Iowa: Iowa State University Press, 1971.

25. Orchard, D. F. *Concrete Technology*, Vol. 1. 4th ed. London: Applied Science Publishers Ltd., 1979.

26. Meyers, S. L. "Thermal Coefficient of Expansion of Portland Cement - Long-time Tests." *Industrial and Engineering Chemistry*, Vol. 32 (1940), pp. 1107-1112.

27. Cook, H. K. "Concrete Aggregates: Thermal Properties." In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, ASTM STP No. 169-A. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1966, pp. 476-486.

28. Armaghani, Jamshid M. "Comprehensive Analysis of Concrete Pavement Response to Temperature and Load Effects." Ph.D. dissertation, University of Florida, Gainesville, Summer 1987.

29. Bergstrom, Sven G. "Temperature Stresses in Concrete Pavements." *Proceedings of the Swedish Cement and Concrete Research Institute*, No. 14 (1950), pp. 1-37.

30. Touloukian, Yeram Sarkis, R. K. Kirby, R. E. Taylor, and T.Y.R. Lee. *Thermal Expansion--Nonmetallic Solids*, Volume 13. New York: IFI/Plenum of Plenum Publishing Corporation, 1977.

31. Tilley, Donald E. *University Physics for Science & Engineering*. Menlo Park, California: Cummings Publishing Company, Inc., 1976.

32. Herubin, Charles A. & Theodore W. Marotta. *Basic Construction Materials: Materials and Testing*. 3rd ed. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1987.

33. Ostle, B. *Statistics in Research*. 3rd ed. Ames, Iowa: Iowa State University Press, 1963.

34. Constantinides, Ioannis. "Computer-Aided Concrete Mix Design." Unpublished High-honor Report, University of Florida, Gainesville, Summer 1986.

35. ASTM. *Annual Book of ASTM Standards*, Section 4 (Construction), Vol. 04.02 (Concrete and Mineral Aggregates). Philadelphia, Pennsylvania: American Society for Testing and Materials, 1984.

36. Mehta, P. Kumar. *Concrete: Structure, Properties, and Materials*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1986.

37. Cordon, William A. Properties, Evaluation, and Control of Engineering Materials. New York: McGraw-Hill Book Company, 1979.

38. Tia, Mang, David Bloomquist, Prasit Soongswang, Constantinos Meletiou, Ed Dobson, Danny Richardson. "Field and Laboratory Study of Modulus of Rupture and Permeability of Structural Concretes in Florida." Interim Report, University of Florida, Gainesville, Oct. 1987.

39. Anderson, Virgil L. and Robert A. McLean. Design of Experiments-- A Realistic Approach. New York: Marcel Dekker, Inc., 1974.

40. Florida Department of Transportation. Standard Specifications for Road and Bridge Construction. Tallahassee, Florida: Florida Department of Transportation. Edition of 1986.

41. American Concrete Institute. Building Code Requirements for Reinforced Concrete (ACI 318-83) (Revised 1986). Detroit, Michigan: American Concrete Institute, 1987.

42. Ruth, Byron E. Class Notes for ECI 6416: Properties, Design and Control of Concrete. Department of Civil Engineering, University of Florida, Spring 1988.

43. Wang, Chu-kia, and Charles G. Salmon. Reinforced Concrete Design. 4th ed. New York: Harper & Row, Publishers, Inc., 1985.

44. Armaghani, Jamshid M., Torbjorn J. Larsen, and Lawrence L. Smith. "Temperature Response of Concrete Pavements." in Effects of Temperature and Water on Pavement Performance, Transportation Research Record 1121. Washington, D.C.: Transportation Research Board, 1987, pp. 23-33.

45. Yoder, E. J. and M. W. Witzack. Principles of Pavement Design. 2nd ed. New York: John Wiley and Sons, Inc., 1975.

46. Tia, Mang, David Bloomquist, Byron E. Ruth, Chung-Lung Wu, Bouzid Chouban, and Chao-Hun Tang. "Field Evaluation of Rigid Pavements for the Development of a Rigid Pavement Design System--Phase III." Final Report, University of Florida, Gainesville, Florida, September 1988.

SUPPLEMENTARY BIBLIOGRAPHY

American Concrete Institute. Building Code Requirement for Reinforced Concrete (ACI 318-83) (Revised 1986). Detroit, Michigan: American Concrete Institute, 1987.

American Concrete Institute. ACI Manual of Concrete Practice, Part 1. Detroit, Michigan: American Concrete Institute, 1985, pp. 209R-24 to 209R-25.

American Concrete Institute. Behavior of Concrete Under Temperature Extremes, SP-39. Detroit, Michigan: American Concrete Institute 1973.

American Concrete Institute. Temperature and Concrete, SP-25. Detroit, Michigan: American Concrete Institute, 1971.

Anderson, Virgil L. "Restriction Errors for Linear Models (An Aid to Develop Models for Designed Experiments)." Biometrics, Vol. 26, No. 2 (June, 1970), pp. 255-268.

Anderson, Virgil L. and Robert A. McLean. Design of Experiments--A Realistic Approach. New York: Marcel Dekker, Inc., 1974.

Anderson, Virgil L. and Robert A. McLean. "Restriction Errors: Another Dimension in Teaching Experimental Statistics." The American Statistician, Vol. 28, No. 4 (November, 1974), pp. 145-152.

Armaghani, Jamshid M. "Comprehensive Analysis of Concrete Pavement Response to Temperature and Load Effects." Ph.D. dissertation, University of Florida, Gainesville, Summer 1987.

Armaghani, Jamshid M., Torbjorn J. Larsen, and Lawrence L. Smith. "Temperature Response of Concrete Pavements." in Effects of Temperature and Water on Pavement Performance, Transportation Research Record 1121. Washington, D.C.: Transportation Research Board, 1987, pp. 23-33.

ASTM. Annual Book of ASTM Standards, Section 4 (Construction), Vol. 04.02 (Concrete and Mineral Aggregates), Philadelphia, Pennsylvania: American Society for Testing and Materials, 1984.

Bartlett, M. S. "The Use of Transformations." Biometrics, Vol. 3 (1947), pp. 39-52.

Bergstrom, Sven G. "Temperature Stresses in Concrete Pavements." Proceedings of the Swedish Cement and Concrete Research Institute, No. 14 (1950), pp. 1-37.

Berwanger, Carl and A. Faruque Sarkar. "Thermal Expansion of Concrete and Reinforced Concrete." ACI Journal, Title No. 73-52 (November, 1976), pp. 618-621.

Berwanger, Carl and A. Faruque Sarkar. "Effect of Temperature and Age on Thermal Expansion and Modulus of Elasticity of Concrete." In Behavior of Concrete Under Temperature Extremes, Publication SP-39. Detroit, Michigan: American Concrete Institute, 1973, pp. 1-22.

Bonnell, D.G.R. and F. C. Harper. "The Thermal Expansion of Concrete." Journal of the Institution of Civil Engineers, Vol. 33, No. 4 (February 1950), pp. 320-330.

Bonnell, D.G.R. and A. Watson. "An Apparatus for Measuring Small Changes in Linear Dimensions." Journal of Scientific Instruments, Vol. 37, No. 1 (January 1950), pp. 10-12.

Browne, R. D. "Thermal Movement of Concrete." Concrete. The Journal of the Concrete Society (London), Vol. 6, No. 10 (October, 1972), pp. 51-53.

Callan, Edwin J. "Thermal Expansion of Aggregates and Concrete Durability." Journal of the American Concrete Institute, Vol. 23, No. 6 (February, 1952), ACI Proceedings, Vol. 48, pp. 485-504.

Chew, Victor. Department of Statistics, University of Florida. Personal Interview. Summer 1989.

Cochran, W. G. "Some Consequences When the Assumptions for the Analysis of Variance Are Not Satisfied." Biometrics, Vol. 3 (1947), pp. 22-38.

Constantinides, Ioannis. "Computer-Aided Concrete Mix Design." Unpublished High-honor Report, University of Florida, Gainesville, Summer 1986.

Cook, H. K. "Concrete Aggregates: Thermal Properties." In Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP No. 169-A. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1966, pp. 476-486.

Cordon, William A. Properties, Evaluation, and Control of Engineering Materials. New York: McGraw-Hill Book Company, 1979.

Crow, E. L., F. A. Davis, and M. W. Maxfield. Statistics Manual. New York: Dover Publications, Inc., 1960.

Cruz, C. R. and M. Gillen. "Thermal Expansion of Portland Cement Paste, Mortar, and Concrete at High Temperatures" (RD074.01T). Portland Cement Association. 1981.

Davis, Raymond E. "A Summary of Investigations of Volume Changes In Cements, Mortars and Concretes Produced by Causes Other Than Stress." Proceedings of the American Society for Testing Materials, Vol. 30, Part 1 (1930), pp. 668-685.

Dettling, Heinz. "The Thermal Expansion of Hardened Cement Paste, Aggregates, and Concrete." Bulletin No. 164, Berlin, 1964. Available from SLA Translation Center, John Crerar Library, Chicago.

Dixon, John S. Center for Instructional and Research Computing Activities (CIRCA), University of Florida. Personal Interview. Summer 1989.

Eisenhart, C. "The Assumptions Underlying The Analysis of Variance." Biometrics, Vol. 3 (1947), pp. 1-21.

Emanuel, Jack H. and J. Leroy Hulsey. "Prediction of the Thermal Coefficient of Expansion of Concrete." ACI Journal, Title No. 74-14 (April, 1977), pp. 149-155.

Fintel, Mark, ed. Handbook of Concrete Engineering. 2nd ed. New York: Van Nostrand Reinhold Company, 1975.

Florida Department of Transportation. Standard Specifications for Road and Bridge Construction. Edition of 1986. Tallahassee, Florida: Florida Department of Transportation.

Goldbeck, A. T. and F. H. Jackson. "The Expansion and Contraction of Concrete and Concrete Roads." U.S. Dept. of Agriculture, Bulletin No. 532, October 13, 1917, pp. 1-31.

Griffith, John H. "Thermal Expansion of Typical American Rocks." Iowa Engineering Experiment Station, Bulletin 128, Vol. 35, No. 19 (October 7, 1936), pp. 5-36.

Harmathy, T. Z. "Thermal Properties of Concrete at Elevated Temperatures." Journal of Materials, JMLSA, Vol. 5, No. 1 (March, 1970), pp. 47-74.

Hatt, W. K. "The Effect of Moisture on Concrete." Transactions of American Society of Civil Engineers, Vol. 89 (1926), pp. 270-315.

Herubin, Charles A. and Theodore W. Marotta. Basic Construction Materials: Materials and Testing. 3rd ed. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1987.

Hveem, F. N. and Bailey Tremper. "Some Factors Influencing Shrinkage of Concrete Pavements." Journal of the American Concrete Institute, Vol. 28, No. 8 (February, 1957), ACI Proceedings, Vol. 53, pp. 781-789.

Keller, Edward A. Environmental Geology. 2nd ed. Columbus, Ohio: Charles E. Merrill Publishing Co., 1979.

Lydon, F. D., ed. Developments in Concrete Technology - 1. London: Applied Science Publishers Ltd., 1979.

Mahoney, Joe P., R. Gary Hicks, and Newton C. Jackson. Flexible Pavement Design and Rehabilitation Shortcourse, Developed for the Western Direct Federal Division, Federal Highway Administration, March 1988.

Matsumoto, Torata. "A Study of the Effect of Moisture Content Upon the Expansion and Contraction of Plain and Reinforced Concrete." University of Illinois Engineering Experiment Station, Bulletin No. 126 (Dec. 5, 1921), pp. 1-29.

McCuen, Richard H. Statistical Methods for Engineers. Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1985.

Mehta, P. Kumar. Concrete: Structure, Properties, and Materials. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1986.

Meyers, S. L. "Thermal Coefficient of Expansion of Portland Cement - Long-time Tests." Industrial and Engineering Chemistry, Vol. 32 (1940), pp. 1107-1112.

Meyers, S. L. "Thermal Expansion Characteristics of Hardened Cement Paste and of Concrete." Proceedings of Highway Research Board, Vol. 30 (1950), pp. 193-203.

Mindess, Sidney and J. Francis Young. Concrete. New York: Prentice-Hall, 1981.

Mitchell, L. J. "Hardened Concrete: Thermal Properties." In Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM Special Technical Publication No. 169-A. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1966, pp. 202-210.

Mitchell, Leonard J. "Thermal Expansion Tests on Aggregates, Neat Cements, and Concretes." Proceedings of the American Society for Testing Materials, Vol. 53 (1953), pp. 963-977.

Montgomery, Douglas C. Design and Analysis of Experiments. 2nd ed. New York: John Wiley and Sons, Inc., 1983.

Neville, A. M. Properties of Concrete. 3rd ed. Essex, England: Longman Scientific and Technical, 1987; New York: John Wiley & Sons, Inc., 1987.

Neville, Adam M. Hardened Concrete: Physical and Mechanical Aspects. Detroit, Michigan: American Concrete Institute; Ames, Iowa: Iowa State University Press, 1971.

Neville, A. M. and J. J. Brooks. Concrete Technology. New York: John Wiley, 1987.

Norton, Charles L. "Some Thermal Properties of Concrete." Journal of American Society of Mechanical Engineers, Vol. 35, No. 6, (June, 1913), pp. 1011-1021.

Ostle, B. Statistics in Research. 3rd ed. Ames, Iowa: Iowa State University Press, 1963.

Orchard, D. F. Concrete Technology, Vol. 1. 4th ed. London: Applied Science Publishers Ltd., 1979.

Orchard, D. F. Concrete Technology, Vol. 2. 4th ed. London: Applied Science Publishers Ltd., 1979.

Orr, Daivd M. F. "Factorial Experiments in Concrete Research." Journal of the American Concrete Institute, Title No. 69-58, (October, 1972), pp. 619-624.

Parsons, Willard and Walter H. Johnson. "Factors Affecting the Thermal Expansion of Concrete Aggregate Materials." Journal of the American Concrete Institute, Vol. 15, No. 5 (April, 1944), ACI Proceedings, Vol. 40, pp. 457-466.

Pearson, J. C. "A Concrete Failure Attributed to Aggregate of Low Thermal Coefficient." Journal of the Americn Concrete Institute, Vol. 13, No. 1 (September, 1941), ACI Proceedings, Vol. 38, pp. 29-34.

Pence, W. D. "Thermal Coefficient of Expansion of Concrete." Journal of the Western Society of Engineers, Vol. 6 (Nov. and Dec., 1901), pp. 549-575.

Petersen, P. H. "Hardened Concrete: Resistance to High Temperature." In Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP No. 169-A. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1966, pp. 290-297.

Petersen, Roger G. Design and Analysis of Experiments. New York: Marcel Dekker, Inc., 1985.

Philleo, Robert. "Some Physical Properties of Concrete at High Temperatures." Journal of the American Concrete Institute, Title No. 54-47 (April, 1958), pp. 857-864.

Powers, Treval C. "Causes and Control of Volume Change." Journal of the Research and Development Laboratories, Vol. 1, No. 1 (January, 1959), pp. 29-39.

Powers, T. C. and T. L. Brownyard "Studies of the Physical Properties of Hardened Portland Cement Paste," Part 9, Proceedings of American Concrete Institute, Vol. 43 (April 1947), pp. 971-992.

Portland Cement Association. Design and Control of Concrete Mixtures. 12th ed. Skokie, Illinois: Portland Cement Association, 1979.

Ropke, John C. Concrete Problems: Causes and Cures. New York: McGraw-Hill Book Company, 1982.

Ruth, Byron E. Class Notes for ECI 6416: Properties, Design and Control of Concrete. Department of Civil Engineering, University of Florida, Spring 1988.

Saemann, J. C. and G. W. Washa. "Variation of Mortar and Concrete Properties with Temperature." Journal of the American Concrete Institute, Title No. 54-20 (Nov., 1957), pp. 385-395.

Sullivan, P. J. E. "The Effects of Temperature on Concrete." In Developments in Concrete Technology--I. Ed. F. D. Lydon. London: Applied Science Publishers Ltd., 1979. pp. 1-49.

Tia, Mang, David Bloomquist, Byron E. Ruth, Chung-Lung Wu, Bouzid Chouban, and Chao-Hun Tang. "Field Evaluation of Rigid Pavements for the Development of a Rigid Pavement Design System--Phase III." Final Report, University of Florida, Gainesville, Florida, September 1988.

Tia, Mang, David Bloomquist, Prasit Soongswang, Constantinos Meletiou, Ed Dobson, Danny Richardson. "Field and Laboratory Study of Modulus of Rupture and Permeability of Structural Concretes in Florida." Interim Report, University of Florida, Gainesville, Oct. 1987.

Touloukian, Yeram Sarkis, R. K. Kirby, R. E. Taylor, and T. Y. R. Lee. Thermal Expansion--Nonmetallic Solids, Volume 13. New York: IFI/Plenum of Plenum Publishing Corporation, 1977.

Tuma, Jan J. Handbook of Physical Calculations. 2nd ed. New York: McGraw-Hill Book Company, 1983.

Wang, Chu-kia and Charles G. Salmon. Reinforced Concrete Design. 4th ed. New York: Harper & Row, Publishers, Inc., 1985.

Washa, G. "Hardened Concrete: Volume Changes." In Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP No. 169-A. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1966, pp. 189-201.

Willis, T. F. and M. E. De Reus. "Thermal Volume Change and Elasticity of Aggregates and Their Effect on Concrete." Proceedings of the American Society for Testing Materials, Vol. 39 (1939), pp. 919-928.

Yoder, E. J. and M. W. Witzack. *Principles of Pavement Design*. 2nd ed. New York: John Wiley and Sons, Inc., 1975.

BIOGRAPHICAL SKETCH

Gabriel D. Alungbe was born in the village of Nyanya-Ulim, Bekwarra, Ogoja Local Government Area, Cross River State, Nigeria, on April 28, 1958. He received his primary education at St. Edward's (1964-1966) and St. Christopher's (1967-1969) Schools located in Nyanya-Ulim and Abuochiche, respectively. After completing his primary education from the latter in 1969, he was admitted into Mary Knoll Secondary School, Okuku, Ogoja, in 1970 and graduated in mid-1974 with a General Certificate of Education Ordinary Level (G.C.E. O/L).

He taught in four primary schools located in Bekwarra between 1974 and 1977. He volunteered as a teacher in Bekwarra Secondary School.

He was enrolled in the General Certificate of Education Advanced Level (G.C.E. A/L) programme in Mary Knoll College in 1976. In 1977, he was admitted into the then newly established Cross River State School of Basic Studies, Okuku, Ogoja.

Under the government of Cross River State scholarship, he attended the University of Wisconsin, Superior, where he studied pre-engineering from March, 1978, to May, 1979. He graduated with a B.S. in Civil Engineering in February, 1982, from Michigan Technological University, Houghton, Michigan.

He returned to Nigeria in October, 1982. He did his National Youth Service Corps programme with the Plateau Urban Development Board, as a civil engineer.

Armed with a scholarship from the Federal Government of Nigeria, he returned to the United States and entered the University of Missouri, Columbia, in September, 1983, where he graduated with a master's degree in civil engineering in December, 1984.

He did further studies in the University of Missouri, Columbia, in 1985. He worked as a construction project manager with the Facilities Management office in the University of Missouri, Columbia.

He came to the University of Florida in January, 1986, where he is currently studying for a Ph.D. degree in civil engineering.

He worked with the former Bureau of Materials and Research (now Materials Office) of the Florida Department of Transportation, Gainesville from May, 1986, to August, 1987.

Mr. Alungbe has a two-year-old son, Ushie.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Mang Tia

Mang Tia, Chairman
Associate Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David Bloomquist, Cochairman
Assistant Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Byron E. Ruth

Byron E. Ruth
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

A. Khuri

Andrawus I. Khuri
Professor of Statistics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Torbjorn J. Larsen

Torbjorn J. Larsen
State Materials Engineer
Florida Department of Transportation

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1989

W J Shafer

Dean, College of Engineering

Dean, Graduate School

UNIVERSITY OF FLORIDA
3 1262 08556 6981